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Climate Change Impacts on Portuguese Energy System in 2050

An assessment with TIMES model

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SUMÁRIO

As alterações climáticas têm merecido extensas avaliações tanto ao nível de impactes, como de estratégias de mitigação e adaptação, ao nível global e nacional. Têm sido identificadas possíveis interacções entre estes factores, no entanto, a avaliação integrada e quantitativa das mesmas peca por defeito. Utilizando o modelo de optimização TIMES_PT, calibrado e validado para Portugal, avaliam-se nesta tese as interacções entre alterações climáticas, estratégias de mitigação, adaptação e o sistema energético nomeadamente em dois sectores em cujo efeito das alterações climáticas é mais notório: produção hidroeléctrica e procura de energia útil. Os resultados indicam que é prudente e custo-eficaz adiar a decisão de construção de grandes barragens hidroeléctricas além de 2020 e que a capacidade instalada hidroeléctrica poderá baixar até 15% em 2050 face a um cenário sem alterações climáticas. A entrada de grande potência hídrica pode também comprometer a penetração de tecnologias de produção de electricidade avançadas. No global o sistema energético beneficiará com as alterações climáticas por via da redução da procura de energia útil resultando numa gama entre 4500M€$_{2000}$ e 6100M€$_{2000}$ de poupança acumulada entre 2000 e 2050 face a um cenário sem alterações climáticas.

ABSTRACT

Significant work has been developed in defining climate change impacts, adaptation and mitigation measures both on national and worldwide scopes. In the published literature, strong references are made linking effects of mitigation and adaptation and how the two can counteract, but there is still a lack of integrated assessment of these issues. Using the optimization model TIMES_PT, calibrated and validated for Portugal, interactions between climate change, mitigation strategies, adaptation and the energy system are evaluated in this thesis. A special focus is addressed on two sectors where climate change effects are the most noticeable: hydroelectric production and energy demand. Results indicate that it is wise and cost-effective to delay the investment in new hydropower infrastructure beyond 2020 and that hydropower installed capacity could be reduced in 15% in 2050 when compared with the scenario with no climate change. Furthermore, large hydropower capacity could compromise the deployment of advanced electricity production technologies. Overall, the energy system will benefit from climate change due to useful energy demand reduction, reaching accumulated savings from 4500M€$_{2000}$ to 6100M€$_{2000}$ compared to the no climate change scenario.

List of Acronyms

IPCC	Intergovernmental Panel on Climate Change
EU	European Union
IA	Portuguese Environment Institute
PNAC	National Climate Change Program
DGEG	General Energy and Geology Directorate
DPP	International Relations, Prospective and Planning Department of the Ministry of Environment, Territorial Management and Regional Development
PNBEPH	National Plan for High Potential Hydropower Infrastructures
ETSAP	Energy Technology Systems Analysis Programme
IEA	International Energy Agency
TIMES	The Integrated MARKAL-EFOM system
GAV	Gross Added Value
GDP	Gross Domestic Product
CHP	Combined Heat and Power
NEEDS	New Energy Externalities Developments for Sustainability
EDP	*Energias de Portugal* Portuguese Energy Company
REN	National Energy Grids
CSP	Concentrated Solar Power
IGCC	Integrated Gasification Combined Cycle
GHG	Greenhouse Gases

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1. INTRODUCTION

1.1. Climate Change and Energy Policy

Climate change has been a hot topic of discussion in the international arena for the last 20 years, with increasing importance in the recent years as is proven by increasing legislative and policy options in this domain. The acknowledgement of some of the possible impacts of climate change lead the international community to create, in 1988, the IPCC (Intergovernmental Panel on Climate Change) in order to provide policymakers with objective and scientific information that guides policy action. The latest IPCC report (IPCC Fourth Assessment Report: Climate Change 2007) which collects scientific, technical and socio-economic information relevant for the understanding of human induced climate change, has clearly stated that *observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases* and *most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG* (Greenhouse Gases) *concentrations* (IPCC, 2007). One of the main sources of GHG is the energy sector as a consequence of fossil fuel burning.

Having this in mind, a growing concern has been taken in energy policy planning by integrating GHG reduction measures (along side with energy security concerns and energy dependency reduction). A clear example of what has been stated is the, currently in discussion, EU (European Union) energy policy (Climate and Energy Package) targeting clear objectives on the use of energy from renewable sources, GHG reductions and energy efficiency[1].

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[1] The European Council has set two key targets for the EU: a reduction of 20% (relative to 1990 levels of emission) in greenhouse gases and a 20% share of renewables in EU energy consumption by 2020, coupled with a target of saving 20% of energy consumption (EC, 2008).

Although climate change strategies have been thoroughly dedicated to mitigation of climate change by reducing greenhouse gases, significant concern is starting to arise on the adaptation measures needed to cope with unavoidable climate change effects[2].

In Portugal, evaluating climate change impacts has been a consistent task developed by the Climate Change Impacts, Adaptation and Mitigation Unit of the Foundation of the Faculty of Sciences of the University of Lisbon. This group has published two reports evaluating climate change scenarios, impacts and adaptation measures in Portugal for the following topics: Water Resources, Coastal Zones, Agriculture, Human Health, Energy, Forests and Biodiversity and Fisheries. Regarding the energy sector two main conclusions are highlighted: on the supply side, it was not clear how hydropower electricity production could be affected with changes in precipitation and, on the demand side, an increase in global energy demand in residential and commercial is expected due to increasing cooling needs (despite a predictable decrease in heating needs) (Santos et al, 2006).

Following the evidences of human induced climate change and subsequent need to act and also in order to comply with the EU legislation, Portuguese energy sector is being developed with strong emphasis on mitigation of climate change. A national climate change program (PNAC – IA, 2006a) is currently in place with a relevant part of the mitigation measures dedicated to the energy sector; renewable electricity is a growing sector (53% increase in installed capacity from 2001 to 2007)[3]; a national plan on high potential hydroelectric dams (PNBEPH – INAG, 2007) envisages a steep growth (46% in 2020 relative to 2005) in hydropower installed capacity; and,

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[2] Mitigation: An anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases (IPCC, 2001). Adaptation: Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (IPCC, 2001).

[3] It should be noted that electricity production from renewables is highly dependent on hydropower productivity which has strong variations between years. Also note that the share of renewables, in real terms, on electricity production profile in 2000 and 2006 (years with similar hydro productivity index) is equal – 30,6% (DGEG, 2008a).

most recently, a national action plan on energy efficiency (PNAEE – DGEG, 2008b) has been legislated. The framework for all these plans is the national energy strategy (MEI, 2008) which has three main objectives: ensure security of energy supply, promote competition and ensure the environmental performance of the energy system.

1.2. Problem Definition

Significant work has been developed in defining climate change impacts, adaptation and mitigation measures both on national and worldwide scopes. On a global scale IPCC reports developed and compiled significant literature on all these aspects. On a national level SIAM project (Santos et al, 2006 and 2002) developed two reports, the latest one dated from 2006, downscaling IPCC methodologies to Portugal and developing new ones in order to identify the main issues regarding climate change. On both the IPCC and SIAM reports, strong references are made linking effects of mitigation and adaptation and how the two can counteract. In fact, the Fourth Assessment Report Working Group II included a whole chapter dedicated to this subject (Klein et al, 2007).

For instance, hydropower is seen as one of the most promising options to increase renewable electricity production share[4] but, as will be demonstrated later, production potential can be seriously undermined by reduced water availability as a result of climate change (Sims et al, 2007). Can the latter effect compromise mitigation potential of this technology? Some assessment has been done in identifying possible counteractions but there is still a lack of integrated assessment of these issues. The same is true for energy demand: reducing energy demand is seen as a mitigation measure but energy demand can be strongly influenced by climate change with changes in temperatures and consequent shifts in needs for heating and cooling.

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[4] The IPCC 4th Assessment Report points out that 85% of unexplored hydroelectric potential from OCDE countries can reduce CO_2 emissions with a negative marginal abatement cost. (SIMS *et al*, 2007)

Which is the most efficient option for reducing CO_2 emissions under climate change scenarios: strong investment on hydropower or investment in other technologies? How can climate change affect energy demand? Does the projected increase in cooling demand surpass the reduction in heating demand? How do energy supply and demand relate under climate change scenarios and a CO_2 constrained world? These are some questions that require a quantitative assessment in order to better support policy decision in a highly uncertain future. Figure 1.1 represents a scheme of the interactions between all these factors, which will be subject to evaluation throughout the remaining of this work.

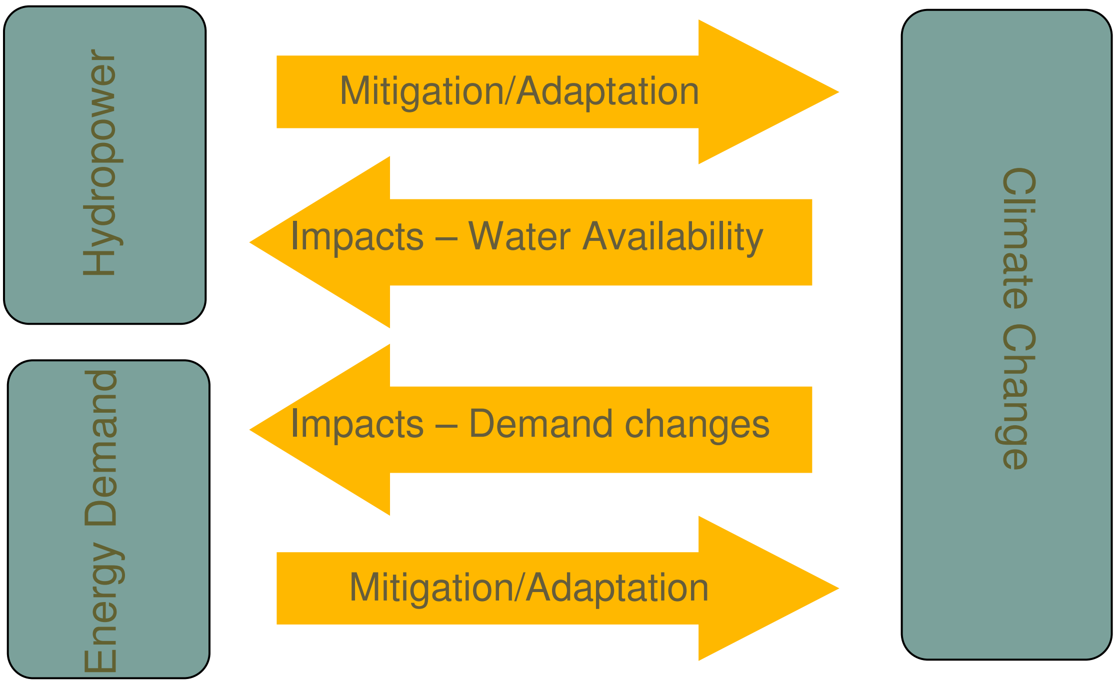

Figure 1.1 - Cross-effects between climate change, hydropower and energy demand

In order to evaluate these impacts and cross-effects a reasonable timeframe for modelling has to be defined. On the one hand, long term analysis (2070-2100) is the best option for evaluating climate change impacts since these are stronger on longer periods; on the other hand, defining energy demand on the long term is an exercise that requires defining scenarios that take into account different possibilities of economical and social organization. In order to have useful results on the medium term that could be used for present policy decisions it was decided to set as a target the year 2050 as a compromise solution. This enables to evaluate some of the impacts that are already expected for the year 2050 and derive, although with some uncertainty, a reasonable evolution of useful energy demands (although this would be far more accurate on the 2020-2030 timeframe).

Two key sectors of the energy system will be evaluated in the present work: hydropower – since SIAM's evaluation of impacts on this sector was not conclusive – and energy demand in residential and commercial sector – since SIAM concluded that this could be the most affected sector by climate change.

Regarding hydropower, traditionally, its design and policy have been based on the assumption of stationary hydrology, regarding the principle that the past conditions will remain to the future. This is confirmed in the PNBEPH which makes no reference to future hydrological conditions under climate change. This assumption should be revised, under climate change scenarios knowledge, in order to avoid excessive costs or poor performance (Kundzewicz et al , 2007).

The ultimate objective of the presented work is the assessment of the impacts on the Portuguese energy system due to climate change induced water availability variations, with a special focus on the electricity production sector, coupled with the evaluation of impacts on useful energy demand requirements under increasing temperature scenarios. It is also an objective to evaluate the effectiveness of currently planned hydropower capacity for Portugal and ultimately produce recommendations that could be useful for policy in the decision-making process of energy planning. It should be stressed out that it is not a main objective of this work to present a forecast for 2050, but to define a reference scenario that could be compared with climate change scenarios in order to evaluate its impacts.

2. METHODOLOGY

Evaluating the whole of the energy system is an enormous task due to feedbacks between these system components (supply, demand and transformation). Most of the evaluation of the EU energy policy targets has been carried out with powerful modelling tools[5] (Russ et al, 2007), which allow a comprehensive and integrated approach of the impacts of the policy both in the energy system and macroeconomic behaviour to these targets. One type of models used consistently in evaluating energy systems, are the top-down models: these use microeconomic theory, under a partial equilibrium, to assess changes under different scenarios, being exceptionally detailed regarding the technological database. For the purpose of this work one such model is used: TIMES_PT[6] is a linear optimisation bottom-up technology model generated with TIMES[7] model generator. TIMES was developed by the ETSAP (Energy Technology Systems Analysis Programme) of the IEA (International Energy Agency). The generic model structure can be adapted to simulate a particular energy system, which may be local, national or multi regional. TIMES models are widely used to evaluate the impact of energy and environment policies and to perform technological assessments (Tosato, 2006).

The first step of the methodology included the enhancement of the TIMES_PT model technology database regarding hydropower plants. Inputs for TIMES_PT (availability factors for hydropower and useful energy demand in residential and commercial

[5] For a broader picture on types of models used to assess climate change costs see the third IPCC assessment report, Working Group III: Mitigation – Cost Methodologies

[6] The implementation of the TIMES model for Portugal has been undertaken within the several EU research project NEEDS – New Energy Externalities Developments for Sustainability (www.needs-project.org) and RES2020 - Monitoring and evaluation of the RES directives implementation in EU27 and policy recommendations for 2020 (www.res2020.eu) and national funded projects such as E2POL - Integrated Environmental and Energy Policies (http://air.dcea.fct.unl.pt/projects/e2pol/) and PortugalClima2020 – *Avaliação do impacto da Proposta Energia-Clima da CE para Portugal* [Impact evaluation of the EU climate and energy package in Portugal] (www.maotdr.gov.pt).

[7] Acronym for The Integrated MARKAL-EFOM system. TIMES is the successor of two older ETSAP bottom-up energy models: Markal – MARKet Allocation Model and EFOM - Energy Flow Optimisation Model, developed in the 80's.

sectors) were then changed accordingly to each climate change scenarios and ultimately a comprehensive analysis of the different scenarios results was performed. Figure 2.1 shows the wide structure of the methodology. Each step will be carefully detailed in this section.

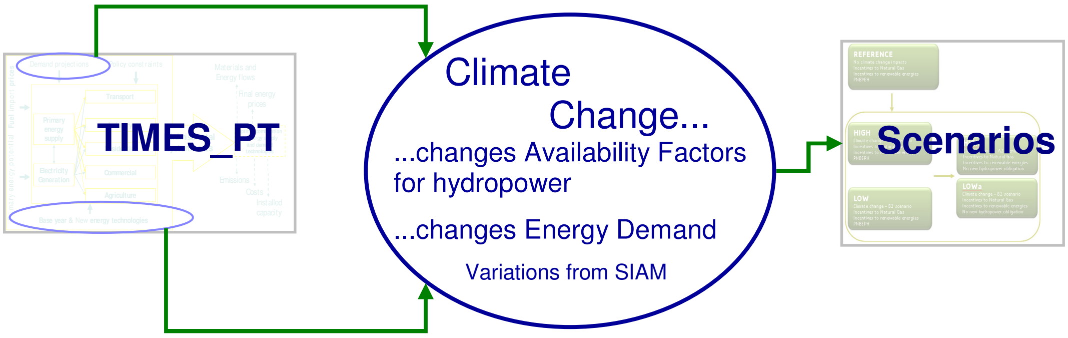

Figure 2.1 - Generic methodology to assess climate change impacts on the Portuguese energy system

2.1. TIMES_PT model

The ultimate objective of a TIMES model is the satisfaction of the energy services demand at the minimum system cost and complying with a series of internal restrictions which express the physical and logical relationships that must be satisfied in order to properly depict the associated energy system (e.g. commodity balance - Gasoline consumed by vehicles plus gasoline exported to other regions must not exceed gasoline produced from refineries plus gasoline imported from other regions). Besides the internal restrictions the user can also set the so-called user constraints that define, for instance, political goals or resources potential (e.g. total emissions of CO_2 must not exceed a certain amount or total installed capacity of hydropower must not exceed 9 GW). For reaching the objective function (satisfying energy demand at the minimum system cost) complying with the restrictions, TIMES simultaneously decides on equipment investment and operation, primary energy supply and energy trade, according to the equation 1 (Loulou *et al*, 2005a).

$$NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} (1+d_{r,y})^{REFYR-y} \bullet ANNCOST(r,y) \quad (1)$$

NPV: net present value of the total costs
ANNCOST: Total annual cost
d: general discount rate
r: region
y: years
REFYR: reference year for discounting
YEARS: set of years for which there are costs

For each year, the TIMES model computes the discounted sum of the annual costs minus revenues. In the case of TIMES_PT, both investment costs and fix and variable operation and maintenance costs of the energy supply and demand technologies are considered. Energy taxes are also included in the model, namely the ISP which is the tax on oil products and other energy carriers and is differentiated by energy carrier. The revenues usually considered within TIMES models include subsidies, recuperation of sunken material and salvage value. However, these are not included in TIMES_PT. More information on TIMES development and equations can be found in Loulou e*t al* (2005a and 2005b).

2.1.1. TIMES_PT Model structure

TIMES_PT represents the Portuguese energy system from 2000 to 2050. The following sectors are modelled: primary energy supply; electricity generation; industry; residential; commercial; agriculture, and transport. Energy, materials and monetary flows, energy demand and supply technologies are modelled in detail, including mass balances. The model structure for the Portuguese system, presented in Figure 1, was adjusted from the model structure developed under the NEEDS[8] project.

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[8] NEEDS – New Energy Externalities Developments for Sustainability (www.needs-project.org)

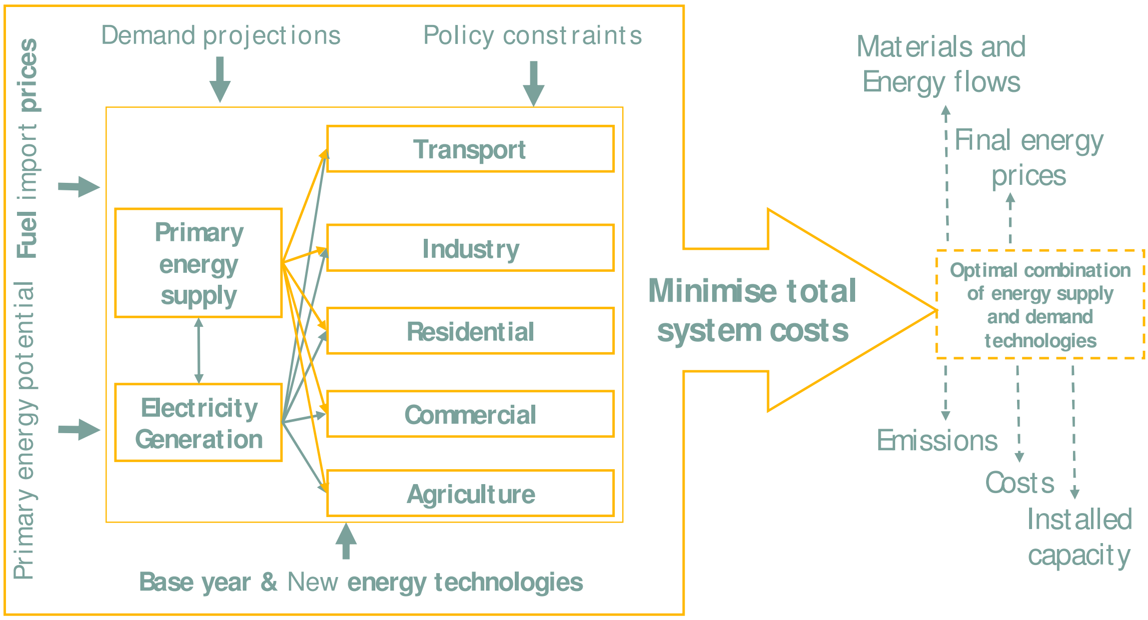

Figure 2.2 - TIMES_PT scheme of the model structure (Source: Simões et al, 2008)

The implementation of TIMES_PT is supported by a detailed database, with the following exogenous inputs: (1) end-use energy services and materials demands, such as residential lighting, machine drive requirements or steel; (2) characteristics of the existing and future energy related technologies, such as efficiency, stock, availability, investment costs, operation and maintenance costs, or discount rate; (3) present and future sources of primary energy supply and their potentials; and (4) policy constraints, such as emission ceilings or energy taxes.

The TIMES_PT model finds the optimum combination of energy supply and demand technologies to satisfy the demand, i.e. the model designs an energy system with the lowest possible total costs. Thus, the main model outputs include the installed capacity of the different technologies, its greenhouse gas emissions, primary and final energy and material flows, final energy prices and, as mentioned, overall system costs.

It should be noted that TIMES_PT is a partial equilibrium model, and thus does not model the economic interactions outside of the energy sector. Among other limitations of these types of models, it does not assume technology R&D costs nor considers in detail demand curves and non-rational aspects that condition investment in new, more efficient technologies, such as preferences motivated by aesthetics or social status. The model assumes that stakeholders have perfect market foresight.

2.1.2. Energy and materials demand projection

The demand projection of energy and materials is an essential input to the TIMES_PT model since it is the driving force of the final demand which the model has to supply. For the purposes of this work, demand evolution was basically retrieved from the work done in the project PortugalClima2020 - Impact evaluation of the EU climate and energy package in Portugal (MAOTDR, 2008) and is thoroughly described in Fortes et al, 2008. Under this framework two different demand scenarios were built: trend and change. The first has the assumption of moderate economic growth and the latter assumes a higher economic growth and a more disruptive economy with strong emphasis on a shift towards innovation and technology. For the purposes of the work hereby presented, the trend scenario was taken since it represents more adequately the basis for a reference scenario that could then be changed in order to include climate change impacts on the energy system.

The broad methodology for calculating energy and materials projections was firstly based on the macroeconomic scenarios prepared by DPP - International Relations, Prospective and Planning Department of the Ministry of Environment, Territorial Management and Regional Development (Ribeiro et al, 2008). From these scenarios a set of comprehensive economic parameters were taken such as sectoral gross added value (GAV), private consumption and gross national product. Each sector had its specific methodology; For example, industry has the associated GAV as a driver but associated with elasticities and residential sector has population and household growth coupled with assumptions in increase in thermal comfort.

The final demand parameter is differentiated across sectors:

- Industry: i) quantities of steel, paper, glass, cement, lime, ammonia and chlorine ii) Useful energy for the remaining industries (ceramics, chemical, other industry)
- Residential: useful energy demand for hot water, cooling and heating, lighting, cooking, refrigeration, cloth washing and drying, dish washing and other electric appliances.
- Commercial: useful energy demand for hot water, cooling and heating, lighting, public lightning, cooking, refrigeration and other electric appliances.
- Transport: passengers and freight transportation trough road, railway, aviation and navigation expressed in pkm (passengers.kilometer) and tkm (ton.kilometer)

The demand generated for PortugalClima2020 was only available until 2030, therefore it was necessary to extrapolate it until 2050, since only in this period climate change impacts begin to be noticeable[9]. The basic methodology to do so was to apply the macroeconomic growth rate from 2020 – 2030 in the remaining period. Although this simplified approach can introduce extra uncertainty to the energy demand, it was out of the scope of the present work to develop new energy demand from scratch.

Figure 2.3 shows the aggregated results for demand growth in key sectors for the scope of this work. Detailed data on final energy and materials demand for all sectors and subsectors can be found in Annex I.

[9] Climate change impacts are normally evaluated for the period 2070-2100 although some impacts are also calculated for 2050 (Santos et al, 2006 and Kundzewicz et al, 2007)

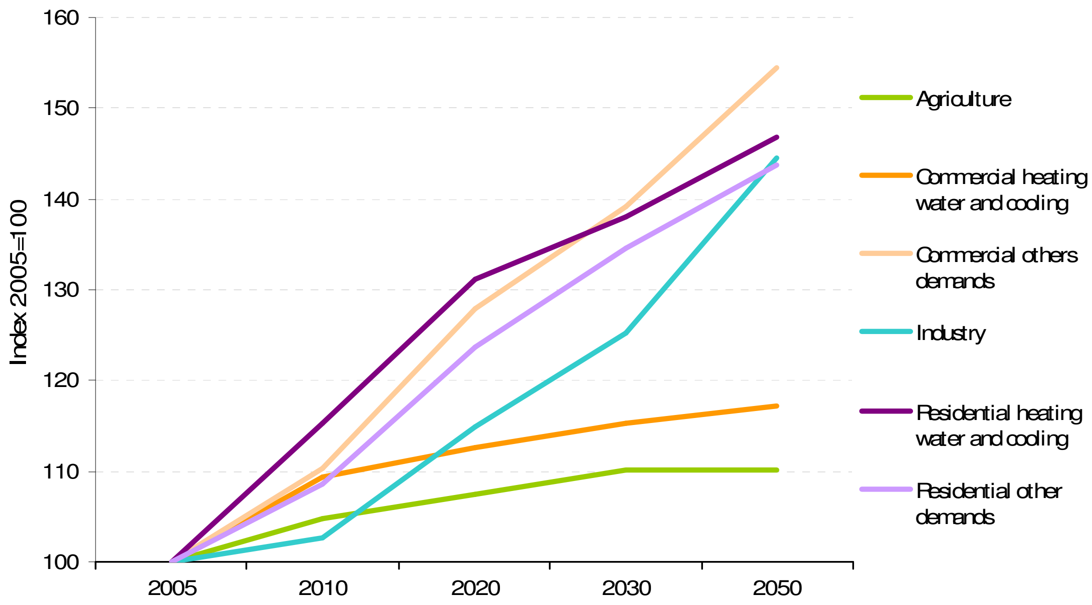

Figure 2.3 - Aggregated final energy and materials demand growth evolution (2005=100)

2.1.3. Technology database (base year and new technologies)

The energy supply and demand technologies for the base-year (2000) were characterised considering the energy consumption data from EUROSTAT and the official DGGE national energy balance to set sector specific energy balances to which technologies profile must comply. Information on installed capacity, efficiency, availability factor, and input/output ratio were introduced using diverse national sources (IA, 2006a; CELPA, 2003; DGGE, 2005; EDP, 2002; EDM, 2005; ERSE, 2001; ERSE, 2006; IGM, 2000; INETI, 2003; INE, 2000; LIPOR, 2005; REN, 2005; REN, 2006; SEIA, 2000; PEGOP, 2005; Turbogás, 2005; Valorsul, 2005). This was followed by a bottom-up approach that adjusted the technologies specifications to achieve coherence with official energy statistics. This bottom-up approach was very relevant for the residential and commercial sectors, for which there is less detailed information on existing technologies.

The energy supply and demand technologies beyond the base year are compiled in an extensive database with detailed technical and economic characteristics of new energy technologies. Some examples for the electricity and the transport sector of the available technologies are given to reflect the detail underlying on such a database:

- Electricity & Heat sector – 89 technologies:
  - 34 different CHP (Combined Heat and Power) technologies reflecting different fuel inputs, capacity sizes and boiler/turbine types (E.g. hydrogen solid oxide fuel cell, biomass integrated gasification combined cycle)
  - 55 centralized power plants (E.g. combined cycle natural gas, geothermal hot dry rock, concentrating solar power, coal integrated gasification combined cycle with CO_2 sequestration, wind off-shore, wave energy)
- Transport sector 83 different technologies (from gasoline engines to hybrid cars to gaseous or liquid hydrogen fuel cell cars) with specifications on use (long distance, short distance) and mode (bus, car, motorcycle, truck, passengers train, freight train, aviation, navigation)

This was developed within the NEEDS project and validated with Portuguese stakeholders for industry, electricity generation, and solar technologies. The validation of the database for the Portuguese case implied also significant changes to the original NEEDS database on new technologies, adding specific technologies that are quite reasonable on the long term for Portugal (e.g. solar heat for industry) but were not considered under the NEEDS project due to the European scale and framework.

TIMES_PT modelling of end-use of energy services and material requires to breakout fuel consumption by end-use (e.g. clothes washing, process heat). Several data sources were used: data from CIEMAT[10], within the NEEDS project (REE, 1998; MITYC, 2003); National Inventory Report on GHG (IA, 2006b); national studies on renewables (Gonçalves, *et al.*, 2002a e 2002b) and on electricity end-use (Júlio, S. et al., 1997; DGGE/IP-3E, 2004); and the PNAC energy demand scenarios. For the residential sector the load diagram data developed by ADENE the National Energy Agency was used (Enertech *et al.*, 2002). The Spanish load diagram data (REE, 1998) was adopted for the commercial sector since there is no Portuguese specific data. Because it was not possible to breakout the energy demand according to the load diagram for industry and transport due to the lack of information, the model does not consider seasonal or daily demand variations for these sectors.

2.1.4. Endogenous Primary Energy Potentials and Energy Import Prices

For Portugal endogenous primary energy potential solely relate to renewable energy. No fossil fuel is currently being retrieved and it is not expected that it will happen. For the modelling exercise this is quite irrelevant since, even if new fossil reserves are to be found, they should not influence primary energy prices because the contribution would be insignificant. The same does not apply for renewable energy sources which have physical, technical, land occupation or environmental constraints. This must defined in the model to allow for a reasonable use of renewable energy. For instance, wind energy has strong limitations related to wind speed and land-use. In order to determine the potential for each technology or resource a large number of studies were compared. For most resources the potential is given not only having in mind the technical potential but also possible deployment of technologies in the near future. For technologies for which the technical potential is virtually unlimited (e.g. concentrated solar power - CSP) no potential is defined beyond 2030 leaving the

[10] CIEMAT- Centro De Investigaciones Energéticas, Medioambientales y Tecnológicas of the Spanish Ministry of Education and Science – Spain (www.ciemat.es)

system free to deploy as much as needed. Table 2.1 shows primary energy endogenous potential for 2030 and 2050 and respective source.

Table 2.1 – Primary energy endogenous potentials

Primary Energy	Used in 2000	Potential in 2030	Potential in 2050	Reference
Wood products (PJ)[11]	71.70	64.70	64.70	GPPAA- MADRP. 2005. Biomassa e Energias Renováveis na Agricultura Pescas e Florestas- Ponto da Situação 2005 (difference due to statistical errors on base year)
Biogas production (PJ)	0.10	23.21	23.21	GPPAA- MADRP. 2005. Biomassa e Energias Renováveis na Agricultura Pescas e Florestas- Ponto da Situação 2005. Extrapolation of National Climate Change Waste Management Scenarios - PNAC 2006
Municipal Waste (PJ)	7.30	10.00	10.00	Extrapolation of National Climate Change Waste Management Scenarios - PNAC 2006 (assumed more 30% than what was used in 2000)
Industrial Waste - organic sludge and other waste (PJ)	0.00	2.00	2.00	Best Guess
Hydro (GW)	4.52	8.07	8.07	2020: Plano Nacional de Barragens com Elevado Potencial Hidroeléctrico. (National Plan for High Potential Hydropower Infrastructures), November 2007. Available: http://www.inag.pt); 2030: Eurelectric (2006). EURPROG: Programmes and prospects for the European Electricity Sector. Section 3.3.pp. 180. December 2006.
Wind off shore (GW)	0.00	3.38	3.38	2020: Based Água & Ambiente, Eólica offshore com potencial de 1000MW,Jan 2007, pp. 40; based on study by INETI, Unidade de Energia Eólica e dos Oceanos; 2030: Resch, G.et al. (2006). Potentials and cost for renewable electricity in Europe - The Green-X database on dynamic cost-resource curves. Vienna, February. pp. 66
Wind on-shore (GW)	0.08	9.45	9.45	Sá da Costa, A. APREN in van de Toorn, G. (2007). EU TradeWind Work Package 2: Wind Power Scenarios. W.P.2.1:Wind Power Capacity Data Collection. 27. April 2007
Solar for water and space heating (PJ)	0.75	38.01	38.01	Gonçalves, H., Joyce, A., Silva, L. (eds), 2002. [Renewable Energy in Portugal Forum – a contribution towards the energy and environmental policy objectives – solar].

[11] A supply curve for biomass import was built with the following assumptions: 20 PJ could be imported at a cost 50% higher than endogenous biomass and 100 PJ could be imported costing the double of endogenous biomass

Primary Energy	Used in 2000	Potential in 2030	Potential in 2050	Reference
Solar thermal for electricity generation (GW)	0.00	2.40	Unlimited	2005. (REN, Coimbra University). CISEPI: Caracterização de Soluções de Integração Sustentada de Elevados Níveis de Produção Intermitente [Characterisation of Solutions of High Levels of Intermittent Production woth Integrated Sustainability]; 2007. (REN, Coimbra University). EFIPRE - Eficiência energética e integração sustentada de PRE. [Energy efficiency and sustainable integration of special regimen production]
Geothermal (GW)	0.01	0.05	0.05	2010: Extrapolation based on Gonçalves, H., Joyce, A., Silva, L. (eds), 2002. [Renewable Energy in Portugal Forum – a contribution towards the energy and environmental policy objectives – Geothermal]. 2020 = 2030: Expert Guess (assumed more 75% from 2010)
Waves (GW)	0.00	5.00	5.00	2020: 2005. (REN, Coimbra University). CISEPI: Caracterização de Soluções de Integração Sustentada de Elevados Níveis de Produção Intermitente [Characterisation of Solutions of High Levels of Intermittent Production woth Integrated Sustainability]; 2007. (REN, Coimbra University). EFIPRE - Eficiência energética e integração sustentada de PRE. [Energy efficiency and sustainable integration of special regimen production]; 2030: Cruz, J., Sarmento, A. (2004). Energia das Ondas - Introdução aos aspectos tecnológicos, económicos e ambientais. Instituto do Ambiente. D.L. 5/2008
Photovoltaic (GW)	0.00	9.30	Unlimited	2005. (REN, Coimbra University). CISEPI: Caracterização de Soluções de Integração Sustentada de Elevados Níveis de Produção Intermitente [Characterisation of Solutions of High Levels of Intermittent Production woth Integrated Sustainability]; 2007. (REN, Coimbra University). EFIPRE - Eficiência energética e integração sustentada de PRE. [Energy efficiency and sustainable integration of special regimen production]

Energy import prices are a crucial input to every regional energy model. The most up-to-date and consensual data (Table 2.2) comes from IEA in their publication "World Energy Outlook 2007 - China and India Insights" (IEA, 2007). In this publication two alternative international fossil fuels prices are assumed: reference scenario and high growth scenario.

Table 2.2 – International energy price projections

	Real Terms (2000 € prices)		2000	2006	2010	2015	2030	2050*
Reference Scenario	IEA Crude oil imports	barrel	30.0	56.9	54.4	52.8	57.2	63.1
	Natural Gas European imports	m^3	0.1	0.2	0.2	0.22	0.2	0.2
	OECD steam coal imports	tonne	36.0	58.1	51.7	52.5	56.4	61.6
High Growth Scenario	IEA Crude oil imports	barrel	30.0	56.9	59.4	61.6	80.2	105.0
	Natural Gas European imports	m^3	0.1	0.2	0.2	0.3	0.3	0.4
	OECD steam coal imports	tonne	36.0	58.0	53.1	56.2	67.0	81.4

Source: World Energy Outlook, 2007 *2050 values extrapolated using 2015-2030 growth rates.

For the purposes of this work it was decided to use as an input the high growth scenario prices which accounts for a high growth in China's and India's gross domestic product on the time horizon and the introduction of predictable energy and climate policies. This was considered as the most plausible scenario and the one that fits with base assumptions made for energy and materials demand (see section 2.1.2)

2.2. Baseline assumptions, calibration and validation

The model was calibrated for the year 2000 and validated for 2000 and 2005, using the official national energy balances. Model calibration required a set of restrictions:

1. To replicate evolution of electricity imports and exports - affected by interconnection capacity with Spain - increasing maximum limits (imports + exports) were set from 2000 to 2050, in tune with national transmission operator studies (REN, 2008) for increased transmission capacity. Thus, trade uncertainty under the liberalised Iberian electricity market is not considered;
2. A maximum growth was set for new CHP plants in industry, based on historical data and on the sector (national CHP association) future

expectations. Thus, in 2001, 32% of all electricity consumed in industry was from CHP, and in 2010 this figure will be 38%, 45% in 2020 and 50% in 2030. These limitations on maximum CHP reflect real CHP constraints such as geographical proximity of potential end-users of heat;

3. Following the past evolution of the energy profile of the residential, commercial and agriculture, there will be no further penetration of coal in these sectors;
4. Due to resistance to change, imperfect information, and aesthetics or other subjective preferences it is assumed that the shift of some fuels is delayed in the residential and commercial sectors by inertia factors. These were defined a minimum value for the share of fuels on the final energy profile and take into account: 2000 statistics share of fuels on final energy, lifetime of existing technologies and increased use of electricity for comfort reasons.
5. The share of electricity has also minimum enforced in the residential and commercial sectors following the general agreement (Aguiar et al, 2007) that the convenience of use of this form of energy will increase its share even if the price is higher than other alternatives.
6. Only 85% of the residential and commercial sector needs can be met with natural gas, due to geographic and technical limitations (GALP, 2007);
7. No dedicated heat power plants will be implemented – all heat will be produced with CHP - and all new CHP plants are associated with specific demand sectors such as refining, industry, commercial or residential. This follows the current and planned CHP promoting policy.

Besides the above assumptions, the most relevant Portuguese energy policies in place were introduced as follows:

1. A ban on nuclear power due to the political unacceptability of this option in the modelled time horizon;

2. Incentives to natural gas combined cycle power plants following the energy sources diversification policy and support to use of natural gas. This is modelled as a minimum installed capacity of at least 3200 MW from 2010 to 2030;
3. New coal power plants will only be available from 2015 onwards following energy sources diversification policy and support to use of natural gas;
4. It is assumed that "conventional" coal power plants without sequestration will not be implemented from 2015 onwards, following expected GHG control policies;
5. Electricity generation from wood residues will continue at least until the end of the lifetime of plants existing in the year 2000 following forest fire control policies objectives;
6. A minimum of 1.1 GW installed capacity of wind onshore is set up in 2005, following the existing feed-in-tariffs for renewable electricity, although this is not included in the costs of renewable electricity generation technologies in TIMES_PT. This represents 9% of total 2005 installed capacity of 13.55 GW;
7. In 2010 biofuels consumption will be at least 10% of the consumed diesel and gasoline in transport, following the Directive 2003/30/EC - on the promotion of the use of biofuels or other renewable fuels for transport and national policy targets;
8. The tax on energy products, differentiated according to the energy carriers, was included, as presented in Table 2.3.

Table 2.3 – Tax on energy products, according to energy carriers

Energy carriers	Tax on energy products (€/PJ)		
	2001	2005	2010-2050
Coal – RCA, supply & industry	-	0.15	0.16
Coal – electricity & CHP	-	-	-
Oil– residential & commercial	6.68	2.48	3.73
Oil – electricity & CHP	-	-	-
Oil - agriculture	1.63	2.11	2.78
Oil - industry	0.69	0.38	0.38
Gas – RCA[a], supply & industry	0.20	-	-
Gas – electricity & CHP	-	-	-
Gas - transport	0.20	2.60	2.72
LPG – RCA & industry	0.16	1.58	0.69
LPG - transport	8.70	4.52	6.82
Diesel - agriculture	8.98	11.48	14.22
Diesel - transport	6.68	8.54	10.58
Gasoline - transport	11.46	18.04	20.57
Biofuels[12] - transport	8.98	11.48	14.22
Kerosene – transport	-	-	-
Heavy fuel oil - transport	-	-	-
Naphtha - industry	-	-	-
Biomass – all sectors	-	-	-
Electricity – all sectors	-	-	-

2.3. A zoom on hydropower modelling

Technology Specifications

For the purposes of the work here presented, TIMES_PT was enhanced with a better technological database in what concerns hydropower infrastructure, in order to ensure a detailed analysis of each of the new hydropower plants. Prior to this work, TIMES_PT had a simplified approach to this sector assuming installed capacity in 2000 (categorized by run-off-river and dam including mini-hidro). Additional capacity was possible by investment in new plants for which technical and economical

[12] Biodiesel, ethanol, methanol

characteristics were derived from an “average” European hydropower plant as used in the NEEDS project, adapted with data from existing power plants. For assessing total energy system evolution this simplified approach could deliver good results but this no longer applies when the focus is on this specific sector. The projected hydropower investments included in PNBEPH have technical and economical data that largely differs from existing ones in Portugal and from a theoretical “average” European hydropower plant; hence that new data was included.

All the selected dams considered in the PNBEPH were introduced into the model (as well as projects being implemented) and two extra generic technologies were introduced:

- Refurbish – this allows for the maintenance of current installed capacity although providing an associated cost of refurbishment instead of simply assuming that installed capacity will remain with no extra cost.
- Generical – this allows for the model to achieve, if necessary, the total hydro potential (as defined in section 2.1.2) since selected PNBEPH investments plus projects being implemented stay below that potential.

Existing hydro capacity (roughly 4.95 GW in 2007) was kept constant throughout the modelled time horizon, although assuming some refurbishment as plants reach the end their useful lifetime. This assumption comes from the fact that, having in mind past trends and future options, it is not reasonable that existing large hydropower plants will be decommissioned. Existing capacity also aggregates mini-hydro (<10 MW electrical installed capacity) which was not modelled in detail, and increased capacity in the period 2000-2010 was included in the refurbishment category. Figure 2.4 represents the maximum full capacity (having in mind that the full potential cannot be reached in a short term) that the model can chose to implement divided into four categories: existing capacity (existing+refurbishment); projects being implemented; projects selected from PNBEPH; generical dam.

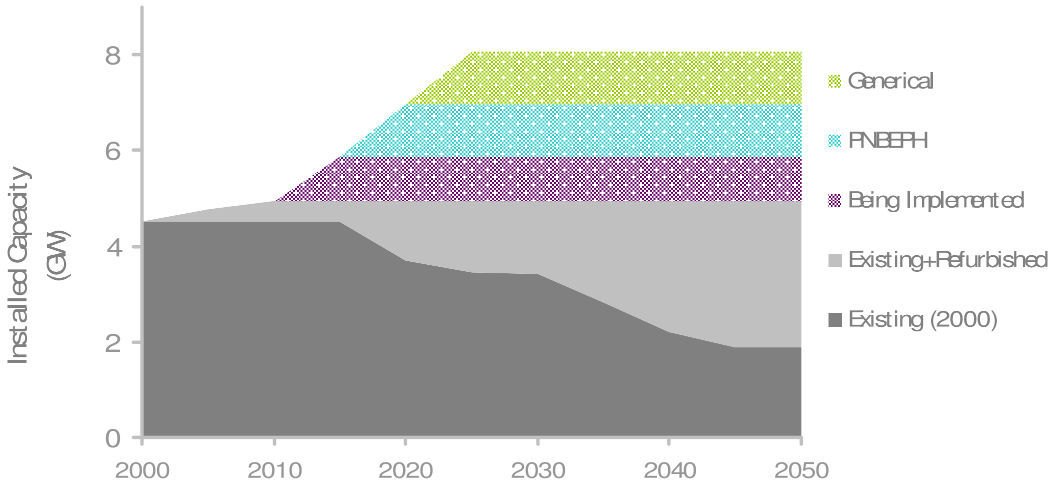

Figure 2.4 - Maximum feasible hydro capacity installation

Technical and Economic Data Sources

TIMES_PT uses, as inputs for economical data of hydro plants, fixed operation and maintenance costs (O&M) and investment costs. For existing hydropower, investment costs are redundant information; O&M data was taken from the NEEDS project and validated by national stakeholders. For projects being implemented, all the data was taken from EDP (www.edp.pt) and PNBEPH (INAG, 2007) was the source for all the new dams. Due to lack of data, it was assumed that refurbishing plants would have an investment cost similar to the cheaper new dam. For the so called "generic" dam it was assumed that costs associated with this technology are at least equal to the costs of the most expensive technology selected in PNBEPH. This assumption reflects the fact that extra dams besides the selected ones in PNBPEH, should have added costs related to either environmental, land-use, social acceptance or other constraints.

As for technical data for hydropower plants, one of the critical parameters is the availability factor. In TIMES, availability factor is defined as the ratio between the electricity output and total possible electricity output if the technology ran at full capacity during a defined timeslice (annual, seasonal, day, night or peak).

Annual availability factors were defined with data from REN - National Energy Grids (www.centrodeinformacao.ren.pt) for existing hydropower plants. For the new hydropower plants, availability factor sources are the same as for the economical data. It was assumed that generical power plants should have an availability factor equal to one representative element of the new power plants from PNBEPH. Vidago hydropower was chosen being the one that is nearer to the average value.

As previously mentioned, timeslice definition may be charaterized between day/night/peak and seasons. For the purpose of hydropower modelling it is crucial to define different availability factors for each season, since hydroelectric production strongly depends on water runoff and precipitation and the latter one differs significantly between annual seasons. Annual availability factor split per season was defined according to REN statistics (www.centrodeinformacao.ren.pt) on electricity production and differently split between Run-of-River (RoR) and Dams for existing power plants. This split share was used as a proxy for all the new power plants also.

Remaining technical parameters are “Lifetime” which reflects useful lifetime of technologies (data from NEEDS) and “Start Year” which sets the year from which the technology is available for the model. It does not reflect the year the technology is implemented but when it can be implemented.

Table 2.4, on the next page, systematizes the data collected and introduced into the model concerning hydropower. For comparison with other technologies see Annex I.

Table 2.4 – Economical and technical data for each hydropower plant

Technology Description	Type	Start	Lifetime	Capacity	Fixed O&M costs	Investment Costs	Maximum Availability Factor Annual	Maximum Availability Factor Fall	Maximum Availability Factor Summer	Maximum Availability Factor Spring	Maximum Availability Factor Winter
			Years	*GW*	*€/kW*	*€/kW*					
Foz Tua	Dam	2015		0.23	9.1	756	0.17	0.13	0.09	0.15	0.27
Padroselos	Dam	2015		0.11	9.6	893	0.10	0.08	0.06	0.09	0.17
Vidago	Dam	2015		0.09	13.1	1178	0.14	0.12	0.08	0.13	0.24
Daivões	Dam	2015		0.11	14.4	1323	0.15	0.12	0.09	0.14	0.25
Fridão	Dam	2015		0.16	9.6	821	0.21	0.17	0.12	0.19	0.34
Gouvães	Dam	2015		0.11	8.8	922	0.16	0.13	0.09	0.14	0.26
Pinhosão	Dam	2015		0.08	13.2	1422	0.16	0.13	0.09	0.14	0.26
Girabolhos	Dam	2015		0.07	14.2	1415	0.16	0.13	0.09	0.14	0.26
Almourol	RoR	2015		0.08	15.4	1229	0.31	0.26	0.16	0.38	0.44
Alvito	Dam	2015	70	0.05	14.0	1385	0.15	0.12	0.08	0.13	0.24
Picote II	Dam	2010		0.23	12.1	584	0.12	0.10	0.07	0.11	0.19
Bemposta II	Dam	2010		0.18	12.1	730	0.10	0.08	0.06	0.09	0.17
Alqueva II	Dam	2010		0.13	12.1	1154	0.00	0.00	0.00	0.00	0.00
Baixo Sabor	Dam	2010		0.17	12.1	2171	0.17	0.13	0.09	0.15	0.27
Ribeiradio	Dam	2010		0.07	12.1	1029	0.16	0.13	0.09	0.15	0.27
Generical	Dam	2010		N/A	15.4	1422	0.14	0.12	0.08	0.13	0.24
Refurbish	Dam/RoR	2001		N/A	9.0	577	0.32	0.27	0.17	0.35	0.50
Existing Dam	Dam	2000		1.77	9.0	577	0.32	0.26	0.18	0.29	0.53
Existing RoR	RoR	2000		2.75	9.0	577	0.33	0.28	0.17	0.40	0.46

2.4. Scenarios Definition

2.4.1. Hydro Availability Scenarios

The hydro availability scenarios were based on the work published under SIAM (Climate Change in Portugal: Scenarios, Impacts, and Adaptation Measures) by the working group on Water Resources (Santos et al, 2002 and 2006). Under this framework, two contrasted IPCC scenarios were chosen for hydro availability scenarios evaluation: A2 and B2. Scenario B2 assumes a return to smaller regional communities, with weaker international links, where the resolution of social problems takes precedence over economical development. Scenario A2 assumes a world increasingly global with a strong economical activity and with diminishing environmental concerns (Cunha et al, 2005). These two scenarios allow assessing the complete range of predictable effects of climate change on hydro resources, with special focus on water run-off. For the purpose of this work, the two hydro scenarios will also be referred as A2 - higher impact of climate change on water availability – and B2 – lower impact of climate change on water availability.

The climatic model chosen, within SIAM, was the GCM HadCM3 developed by the Hadley Centre for Climate Prediction and Research. Water runoff was estimated using the Temez model (Santos et al, 2002 and 2006). Results are disaggregated in five regions: ND – North of Douro, D – Douro, SD – South of Douro, T – Tejo, G - Guadiana; and four seasons: Spring, Winter, Summer and Fall. Although TIMES_PT allows the split across year fractions it does not account for spatial distribution, hence a weighted national average value was considered. Because hydroelectric installed capacity is very different between these three regions (Table 2.5), the impact on hydro availability for electricity production was weighted according to the shares of installed capacity in each region.

Table 2.5 - Water runoff variability (%) in 2050 per region and season

	Region / Season	N	SD	T	G	Weighted Average Water Runoff Variability
		Water runoff variability in 2050 (%)				
Scenario B2	Winter	20	25	27	27	22
	Spring	-8	0	17	10	-3
	Summer	-33	-40	-30	-33	-33
	Fall	-25	-7	-3	55	-16
Scenario A2	Winter	-3	-25	-28	-52	-11
	Spring	-20	-26	-26	-68	-24
	Summer	-50	-50	-50	-68	-51
	Fall	-33	-28	-27	-22	-31
	Installed Capacity	2961 MW	458 MW	484 MW	240 MW	

(ND – North of Douro, D – Douro, SD – South of Douro, T – Tejo, G – Guadiana). Adapted from SIAM (Santos et al, 2002 and 2006)

A simplified approach was adopted by assuming that the share of installed capacity by region remains the same throughout the modelling horizon. Since this share per region is roughly similar to the projected investments of the PNBEPH - National Plan for High Potential Hydropower Infrastructures (INAG, 2007) this simplification will not introduce significant errors. Using water run-off variations as a proxy, the new data on water availability was introduced in 2050 and linearly interpolated between 2020 and 2050.

Simply using water run-off variations as a proxy for water availability on hydropower dams, could introduce significant errors since other factors should be accounted for, such as competition over the use of water (for irrigation for instance) and specific characteristics of the water basins. Hence these results were compared with the ones found on (Lehner et al, 2005). Using a model based analysis of the hydropower potential in Europe, the authors evaluate impacts of precipitation changes due to climate change on electricity production from dams including evaluation of impacts on developed hydropower potential, gross hydropower potential and water competition with other uses. Results suggest that hydropower electricity production could be reduced from -22% to -40% in 2070, which seems coherent with annual reduced availability factors of -8% and -29% (on a annual basis) assumed in the present work for 2050.

2.4.2. Energy Demand Scenarios under Climate Change

Climate Change can strongly impact demand for heating and cooling in residential and commercial sectors. Therefore it was necessary to adapt demand projections referred to in section 2.1.2 in order to have consistency between climate change scenarios for hydro availability and the demand scenarios. Hence, the same general procedure was adopted as in the case of hydro availability scenarios, by selecting the two contrasting scenarios (A2 and B2), for which impacts on energy demand were also determined within SIAM's assessment. The variation on the demand due to climate change was then applied to the demand generated for TIMES_PT.

SIAM's impacts on energy demand are often referred as "long range" (Santos et al, 2002 and 2006) and, although no specific date is defined, a rise in 3-4ºC is suggested as a driving force. This could hamper the direct transposition of these impacts to TIMES_PT for which the time horizon is 2050 if projected impacts in SIAM happened long after this time horizon. Looking at mean temperature anomalies in the Iberian Peninsula obtained with the GCM – Global Circulation Models - data available at the IPPC DDC - data distribution centre (Figure 2.5), it is possible to observe that the 3-4ºC range is likely to be reached in 2050 although most models point to values slightly below 3ºC. Therefore applying the differential SIAM impact to the estimated demand in TIMES_PT might result in slightly overestimated impacts. Even so, these data was used since it is the best available, therefore results should be analysed with caution. It was assumed that only after 2020 climate change impacts start to become visible since until then if some temperature rise occurs it will be meaningless compared to the growing needs of useful energy derived from economical expected growth.

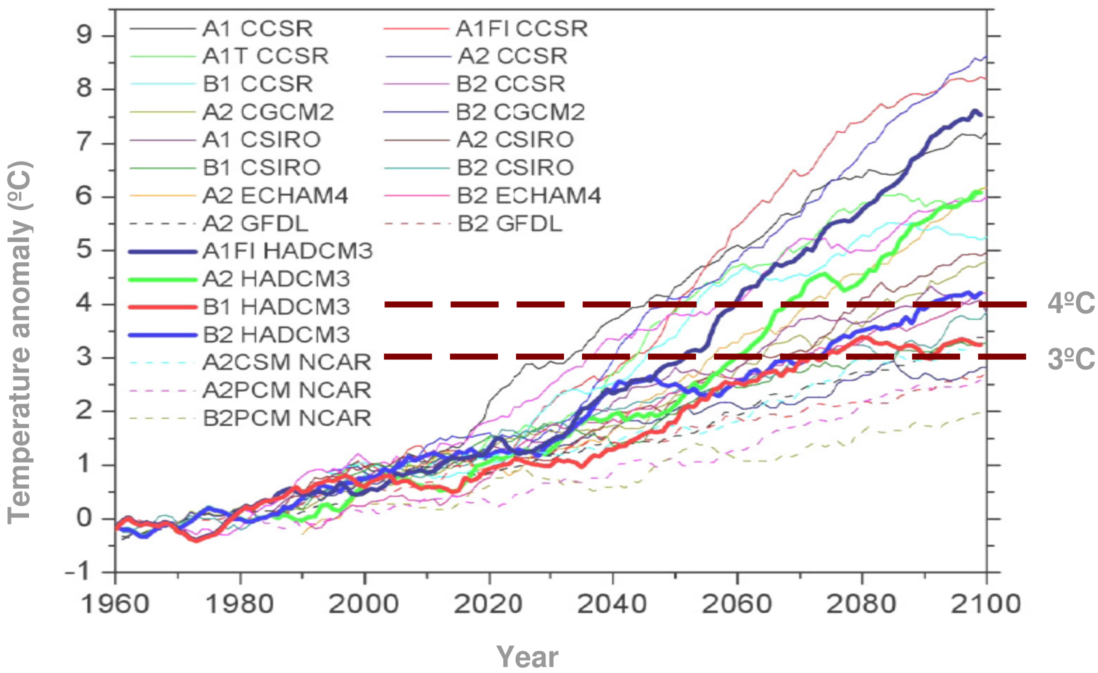

Figure 2.5 – Mean temperature anomaly in the Iberian Peninsula obtained with the Global Circulation Models data available at the IPCC data distribution Centre (source: Santos et al, 2006)

It should be noted that methodologies for demand projections used for SIAM are not fully consistent, as detailed below, with those used for TIMES_PT in absolute terms. However, it was assumed that the relative impact of Climate Change on the demand could be used on top of TIMES_PT demand. Furthermore having different demands has a two-fold objective: firstly, and already mentioned, to consider a consistent energy demand with the climate change scenario analysed; secondly to provide a range of energy demands and therefore provide also some sensitivity analysis (although not fully examined since it will be consistent with the scenario analysed and not evaluated on an individual basis). A full sensitivity analysis would require changing only the demand and checking the impacts on results.

SIAM has identified possible impacts of climate change for water heating, space heating and space cooling both for the residential and commercial sector, disaggregated for North, South and Centre regions of Portugal.

The broad methodology used in SIAM included the selection of representative technologies, type of buildings and end-uses, and the calculation of energy consumption to maintain a specific thermal comfort range. Although assumptions were made, for each socioeconomic scenario, on some parameters like time period spent in houses, the occupancy rate, insulation level, etc. the results are based on theoretical energy requirements to achieve comfort and not actual energy used as in TIMES_PT. The different methodologies lead to different base demands of the respective reference scenarios to which climate change variations will be applied.

After defining the energy demand for each scenario, changes in temperature parameters due to climate change were then applied to derive the new energy demand with climate change impacts. The estimated impacts for each end-use energy demand for the commercial and residential sectors are presented in Table 2.6.

Table 2.6 – Estimated variation (%) to the reference energy demand for the two climate change scenarios (A2 and B2) – Source – adapted from SIAM (Santos et al, 2002 and 2006)

	Unit-%	North		Centre		South		Average	
	Scenario	B2	A2	B2	A2	B2	A2	B2	A2
Residential	Water Heating	-9	-13	-11	-16	-13	-18	-11	-16
	Space Heating	-75	-52	-100	-67	-100	-81	-92	-67
	Space Cooling	+118	+377	+84	+206	+52	+136	+85	+240
Comercial	Water Heating	-9	-13	-11	-16	-13	-18	-11	-16
	Space Heating	-60	-70	-52	-62	-45	-61	-52	-64
	Space Cooling	+34	+66	+38	+60	+112	+161	+61	+96

It is possible to observe that a strong decrease in heating demand is forecasted opposed to a strong increase in cooling demand, reflecting the expected rise in temperatures. In the residential sector it is also possible to see a stronger decrease in demand in the B2 scenario (-92% versus -67% on A2). This might seem counterintuitive, since A2 implies a higher increase in temperatures, but there are other differences between the scenarios that lead to this. In fact, residential demand as calculated in SIAM has the assumption that, in B2 scenario, heating requirements are much lower due to better insulation, behavioral change and better technology. Hence a small increase in temperature has a higher relative impact in the demand.

The average rate of variation was applied to the original demand calculated for TIMES_PT. Although TIMES_PT allows all these different demand categories (even further detailed in rural, urban and multiapartment for residential and large and small for commercial sector), it does not differentiate between regions. Demand projection defined for TIMES_PT accounted for only two regions (north and south) which were then weighted according to number of dwellings in each region. In fact the share of houses for these two regions was roughly 50/50 so it was assumed that the average value of SIAM's regions was a good indicator of predictable climate change impacts. The demand variations were applied to original TIMES demand in 2050 and linearly interpolated between 2020 and 2050. Aggregated demand for useful energy for residential and commercial sectors is shown in Figure 2.6 for the reference scenario and for the scenarios with climate change impact A2 and B2. This was used as input demand data for TIMES_PT model.

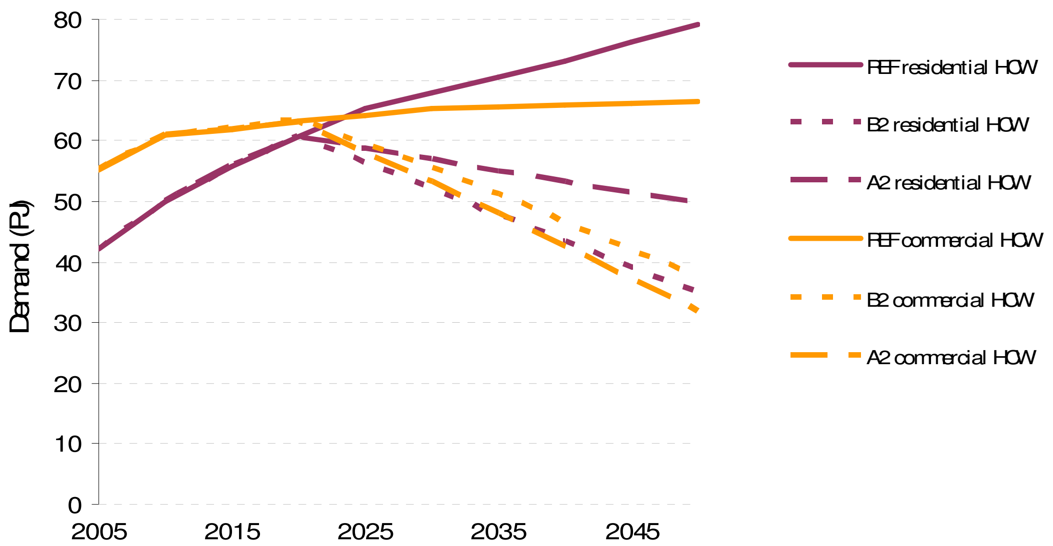

Figure 2.6 - Total energy demand for HCW (space heating, space cooling and water heating) for the residential and commercial sectors on REF and climate change scenarios

The global impact of climate change scenarios refers to a strong reduction (47%) in energy demand: in spite of the increasing demand for cooling, heating bears the lion share of energy demand (in 2050, for the REF scenario heating accounted approximately for 55 PJ in commercial and 48 PJ in residential; cooling accounted only for approximately 4 PJ in commercial sector and 2 PJ in residential sector), hence the decrease forecasted for heating is the driving force for total energy demand reduction. It should be reminded that SIAM's conclusions are the opposite (increase in total energy demand) since the share of the base demand (without climate change) for cooling is much higher than the base demand calculated for TIMES_PT and the steep increase in cooling leads to a global growth in energy demand requirements.

Figures 2.7, 2.8 and 2.9 show the disaggregation for the heating, cooling and water heating demands.

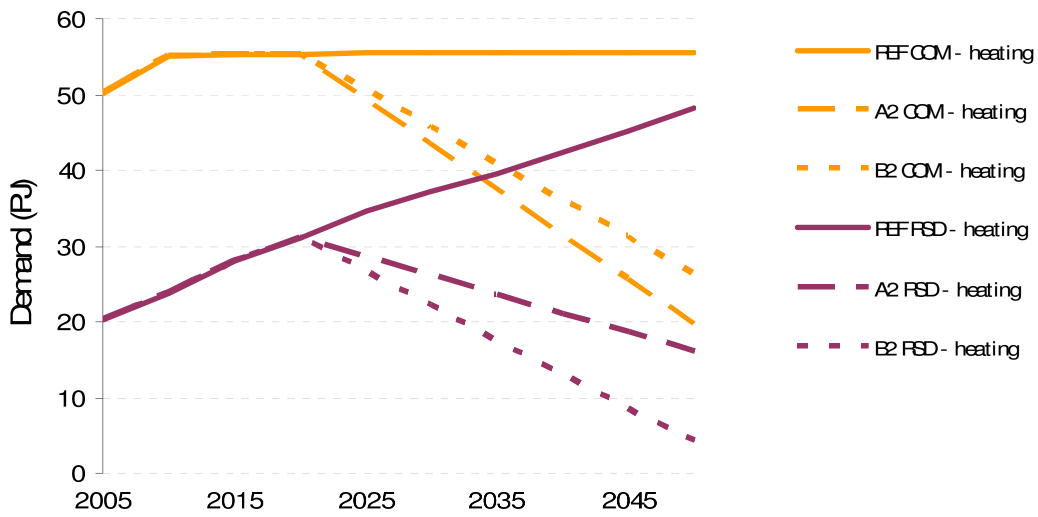

Figure 2.7 - Demand for space heating for the residential and commercial sectors on REF and climate change scenarios

Heating demand is strongly reduced (on average – 69%), as seen on Figure 2.7, and it is possible to observe that in the residential sector reduction is higher in the B2 scenario than in A2 (-92% versus -67% on A2).

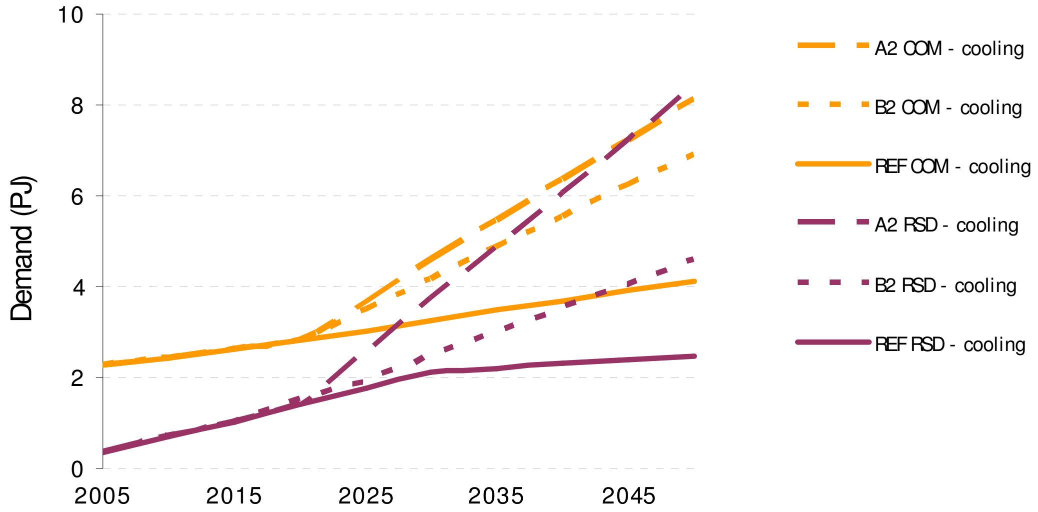

Figure 2.8 - Demand for cooling for the residential and commercial sectors on REF and climate change scenarios

The demand for space cooling steeply increases 122% in average (Figure 2.8) with climate change and this effect is even more pronounced in A2 scenario (increase reaches 240% for residential cooling), driven by higher temperature change and stronger demand for comfort. In A2 scenario, cooling demand for residential rises above 8 PJ even surpassing heating demand (see Figure 2.7).

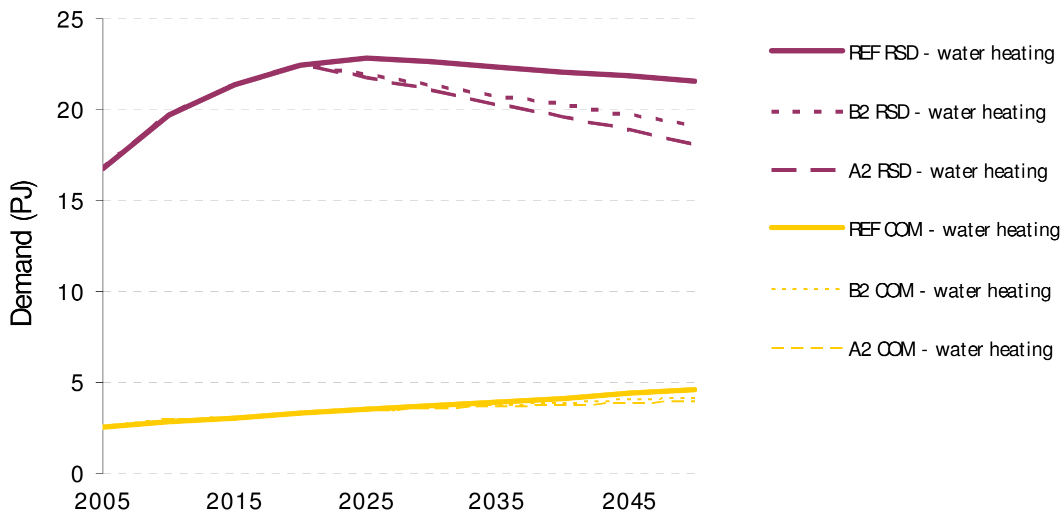

Figure 2.9 - Demand for water heating for the residential and commercial sectors on REF and climate change scenarios

Demand for water heating does not suffer a dramatic impact with climate change, as occurred with other demands. The driving force is the need to heat water from a base temperature that is higher hence there is a reduction in energy use although target temperature and water use remains the same (Santos et al, 2006).

2.4.3. Scenarios for Modelling

A reference case scenario (REF) was built considering the current policies in place in Portugal, specifically the implementation of the projected investments on hydroelectric capacity of the PNBEPH in 2010 and 2020, and support to new combined cycle gas power plants, forcing installed capacity in 2010 as well as minimum capacity constraints for other renewable energy sources. This scenario does not consider any changes on water availability or changes in demand due to climate change.

On top of the reference scenario two alternative climate change scenarios were built: HIGH – high impact of climate change and LOW – Low impact of climate change. HIGH is associated with A2 scenario and LOW with B2 scenario by changing water availability and demand in residential and commercial accordingly (see section 2.4.2), in order to perceive the impact on the energy system of climate change with the policy envisaged. Furthermore, two additional scenarios were built on top of HIGH and LOW but leaving the model the freedom for choosing the amount of new hydropower capacity to install according to cost-efficiency criteria. These will be referred from hereafter as HIGHa and LOWa. The objective of these two later scenarios is to evaluate to which extent projected hydropower investment contributes for the satisfaction of energy demand requirements and CO_2 reductions in a cost effective manner. Figure 2.10 presents a scheme of the different scenarios evaluated, and Table 2.7 systematizes in more detail the scenarios evaluated.

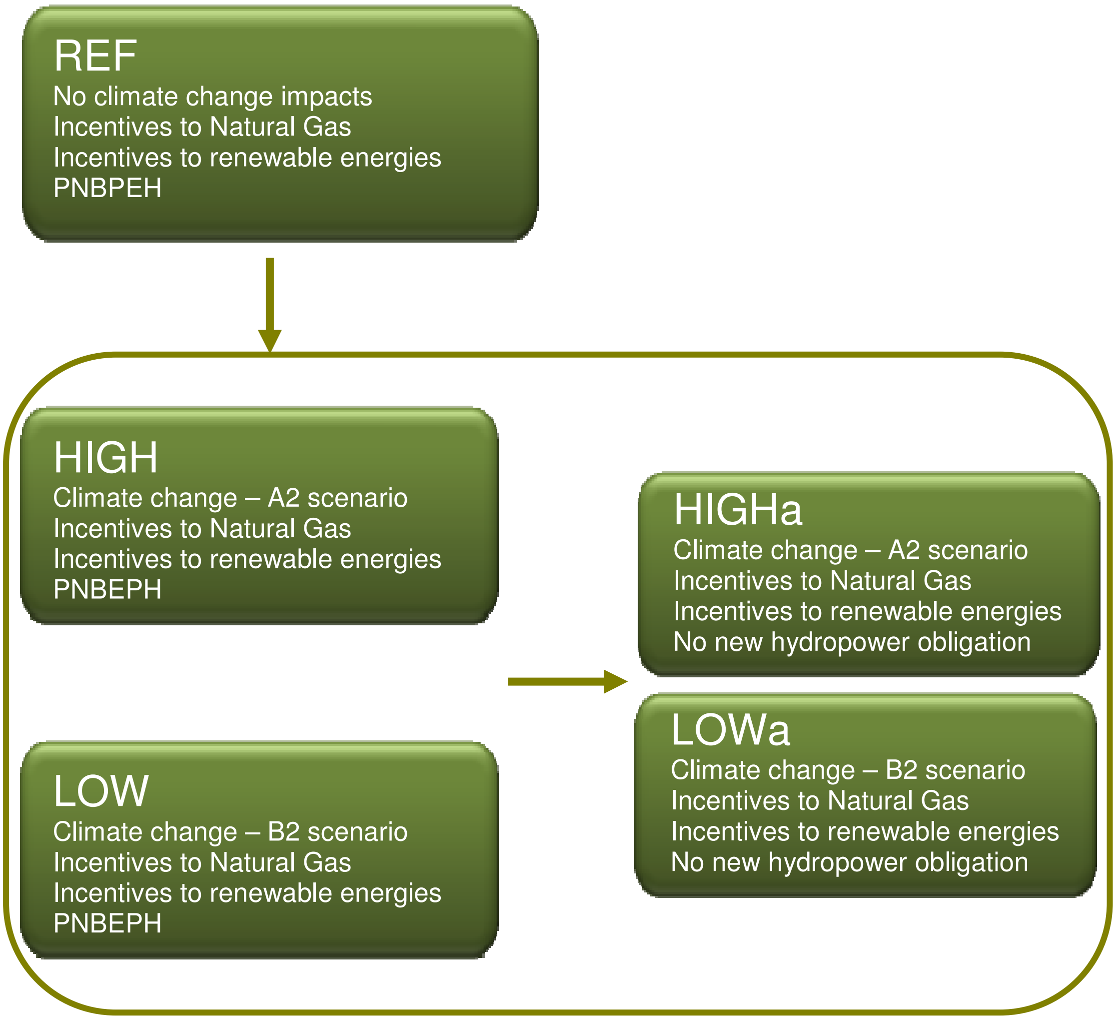

Figure 2.10 - Scheme view of the scenarios analyzed

Table 2.7 – Scenarios analyzed

	Ref	LOW	HIGH	LOWa	HIGHa
Hydro availability	No change	B2 -8% on average	A2 -29% on average	Same as B2	Same as A2
Demand	Base	B2	A2	B2	A2
Forced installed Hydro capacity	Existing + 0.91GW in 2010 + 1.1GW in 2020			Existing only (4.95GW)	
Forced installed Natural Gas capacity	Existing (1.18GW) + 3.20GW in 2010				
Forced installed Renewable Electricity Capacity	5700 MW wind in 2010; 150 MW solar, 150 MW biomass, 100 MW biogas, 250 MW waves in 2010. Minimum capacity kept constant until 2050.				

3. RESULTS AND DISCUSSION

3.1. Reference Scenario

In order to fully understand the behaviour of the model throughout the time horizon an analysis of the reference scenario was chosen since it represents the typical behaviour of the model. Understanding these results is crucial to interpret the impacts and changes induced by climate change over the reference scenario. However, the goal of the study does not focus on the picture at 2050, considered in the reference scenario, but on the analysis of climate change scenarios when compared with it.

3.1.1. Primary energy supply and final energy consumption

Primary energy supply equals production plus imports minus exports of energy commodities. The following categories were considered for the primary energy supply: Electricity, Renewables, Oil Products, Natural Gas and Coal. It usually relates to the energy content of each commodity except for renewable energy sources used for the production of primary electricity. Primary electricity is defined by IEA as the electricity obtained from hydro, wind, solar, tide and wave power. In this case, primary energy is defined as the amount of electricity produced by each of these sources (IEA, 2005). Figure 3.1 shows the evolution of primary energy consumption for the modelled time horizon and the respective GDP energy intensity.

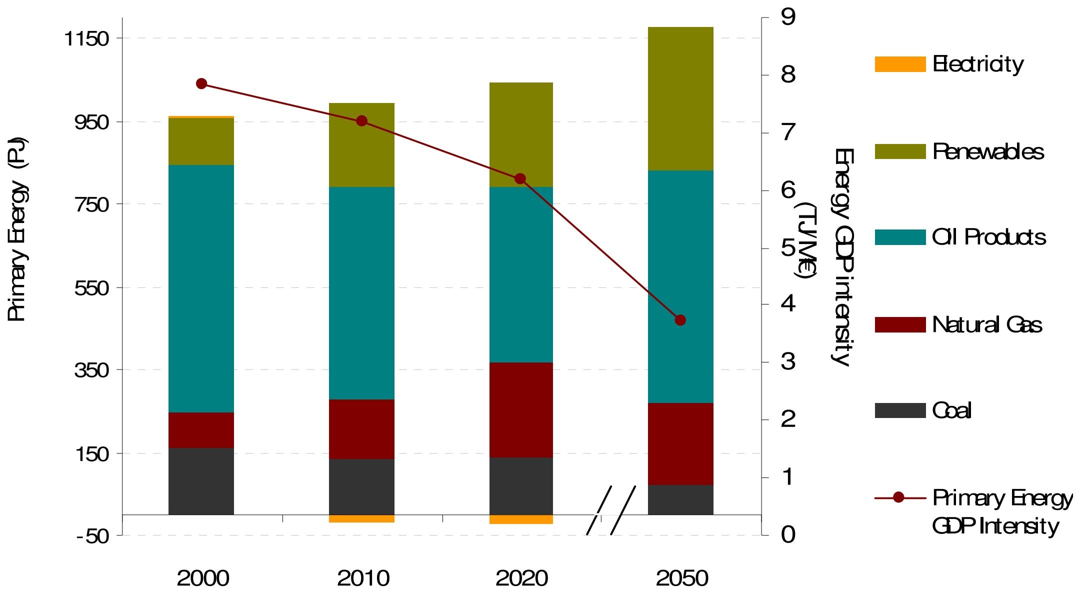

Figure 3.1 - Primary Energy Supply evolution in the REF scenario and primary energy GDP intensity Note: positive values for electricity mean net import; negative values for electricity means net export

It can be seen that, although demand rises quite steeply (on average +42% in 2050 relative to 2000), primary energy supply has a different behaviour with a sustained growth (5% increase in 2020 and 9% in 2050 related to 2000 total primary energy). This behaviour is mainly due to the increasing use of more efficient technologies such as combined cycle natural gas and also due to the increased use of renewable energy sources in the electricity production sector replacing fossil fuels. As mentioned above, primary energy from renewable energy such as hydro, wind, tide or solar are accounted for as the electricity produced. In practice this means that an efficiency of 1 is assumed for renewable technologies which mean more electricity can be produced from less primary energy. This is also quite evident by looking at the energy intensity of GDP (a main driver of energy demand) which decreases roughly by 50% between 2000 and 2050.

It is possible to observe a strong decrease of oil products until 2020 (-29% relative to 2000 values) due to increasing efficient technologies in transport and to fuel switch to diesel and biofuel as well as to the decommissioning of oil power plants. Oil products increase their share from 2020 to 2050 (48% in 2050 *vs* 41% in 2020), mainly due to increasing demand in transports which is no longer compensated with efficiency improvements. Even so the share of oil products is reduced from 62% in 2000 to 48% in 2050. Coal decreases for about half the value of 2000 in 2050 but it should be noted that most of this coal is being used in CCS as can be seen below.

It is also possible to observe a negative value for electricity in 2010 and 2020 which means that Portugal should become a net exporter in these years due to the strong capacity increase for electricity production which surpasses the internal consumption. It should be noted that electricity trade is not modelled as such and these are only the results of excess capacity. Real trade between countries might be quite different but should not be assessed in this framework analysis. After 2020, results suggest that the tendency is for imports and exports of electricity to become equal.

Renewable energy sources gain an important share of primary energy supply (29% in 2050) thus reducing energy dependency rate, which is defined as net imports divided by gross consumption, expressed as a percentage. Values are presented in Table 3.1

Table 3.1 – Energy dependency rate

	2000	**2020**	**2050**
Energy dependency (%)	87%	68%	59%

Final energy consumption refers to all energy used by final consumers in the transport, industry, and other sectors (residential, commerce, public services and agriculture). It excludes oil used for transformation and/or own use by the energy-producing industries (IEA, 2005). Results show (see Figure 3.2) that, overall, electricity (an energy carrier with high efficiency in end-use devices) and natural gas are increasingly used which explains the trend to stabilization of total final energy until 2020 even though useful energy demand increases. The transport sector highly influences the final energy vector mainly in the consumption of oil products.

Beyond 2020, final energy continues to rise driven by energy demand and the fact that the most of the efficient technologies are already in place, hence, buffer for reducing final energy is smaller. Even so, as can be seen in the final energy GDP energy intensity indicator, efficiency plays a big role in reducing the amount of energy used per unit of welfare produced.

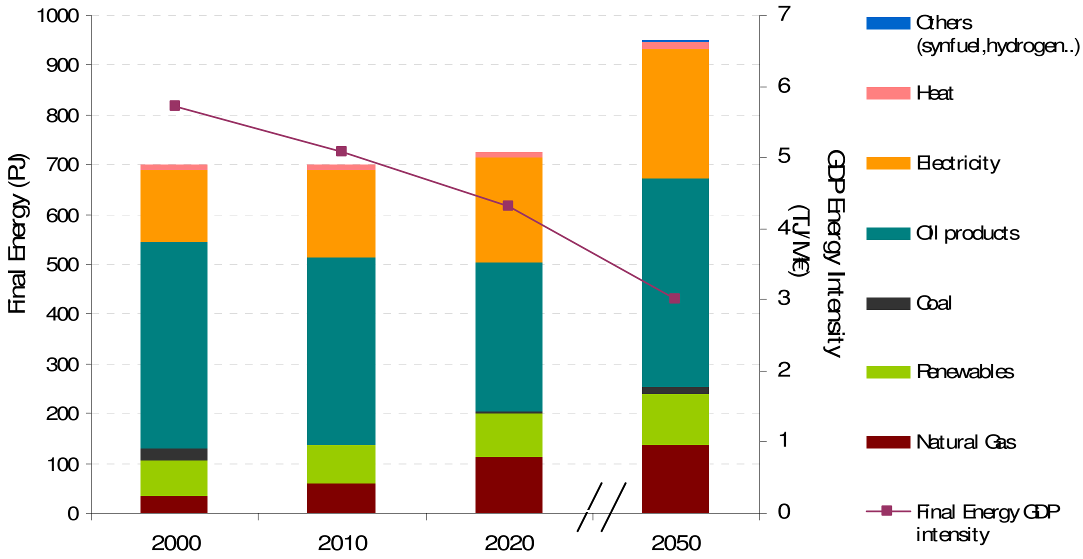

Figure 3.2 - Final energy consumption evolution in the REF scenario and final energy GDP intensity

3.1.2. Final energy consumption in commercial and residential sectors

A detailed analysis of final energy consumption in commercial and residential sectors is presented in this section. Figure 3.3 shows the evolution of final energy consumption on the residential sector. There is a strong growth of final energy consumption (14% in 2020 and 42% in 2050 relative to 2000 values) but even much slower than useful demand growth which rose by 52 to 59% in 2050. This higher efficiency is due to installation of insulation technologies which delivers part of the useful energy demand (represented as a negative value of final energy) and to new efficient technologies, such as heat pumps and high efficiency appliances.

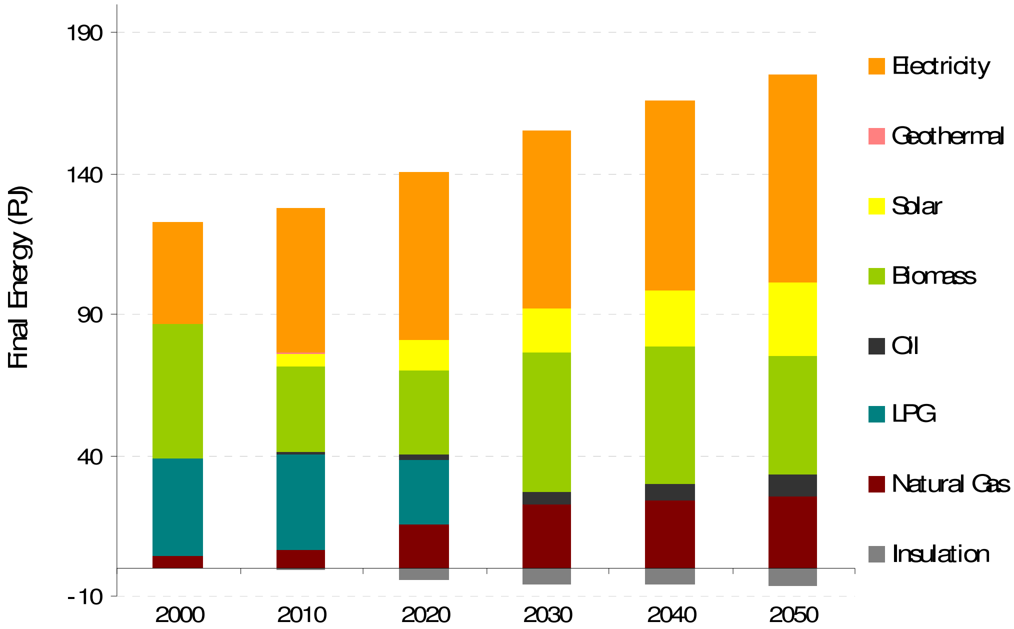

Figure 3.3 - Final energy consumption for residential sector in the REF scenario

There is also a strong penetration of solar panels for water and space heating (0,4% of final energy consumption in 2000, 7% in 2020 and 15% in 2050) which explains the growth in oil consumption. These technologies need backup fuels and part is supported by electricity but some by oil. Natural gas naturally comes into place, especially for cooking, replacing LPG and some biomass. Biomass has a decrease of about 35% in 2010 and 2020 due to its substitution from cooking uses, but gains an important share in the remaining years as it becomes an important fuel for heating in advanced technologies such as thermofireplaces. It should be mentioned that biomass consumption in 2000, which is retrieved from national energy official statistics, might be wrongly estimated since it was extrapolated from an outdated enquiry from1995 (DGEG, 2007). The improvement of energy statistics already envisages the resolution of this problem but at the moment official statistics have not yet been updated.

The commercial sector fuel consumption profile presented in Figure 3.4 is substantially modified throughout the time horizon.

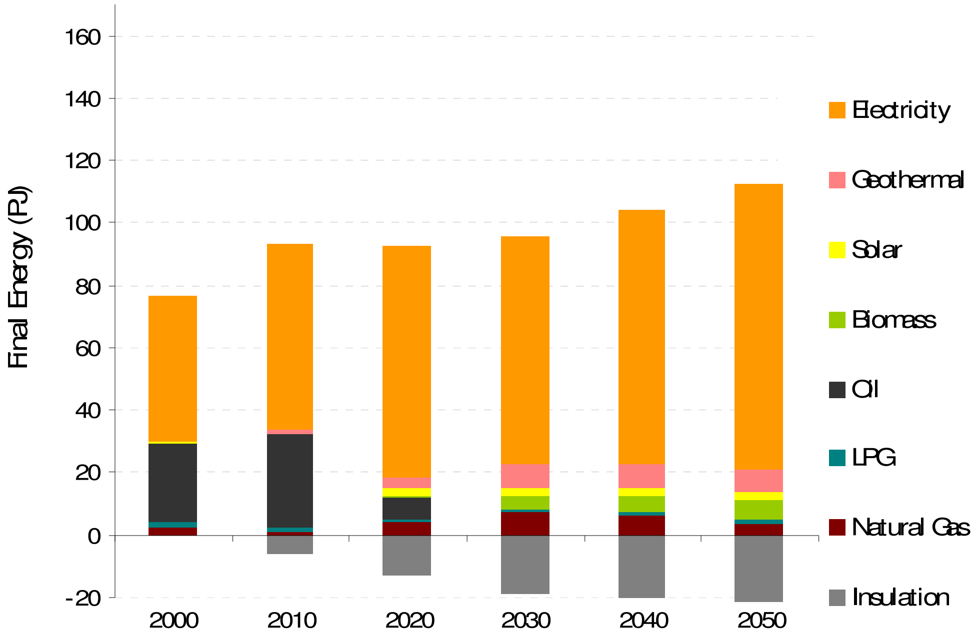

Figure 3.4 - Final energy consumption for commercial sector in the REF scenario

The verified trend to increased use of diesel oil is reversed and new fuels come into place such as biomass, solar and geothermal. Electricity also increases its share mainly due to the fast increasing demand of appliances and also cooling and heating demands. Insulation becomes a major player in satisfying useful energy demand requirements (17% of total useful energy demand in 2050) or, in other words, reducing final energy consumption by useful energy produced.

As in residential sector, increase of useful demand is higher than increase of final energy (demand rises about 40 to 57% and final energy only 17%) due to higher efficient technologies. Increased use of insulation and electricity based technologies imply that by 2050, the commercial sector is almost zero direct CO_2 emissions.

3.1.3. CO_2 Emissions

Emissions here reported are only CO_2 emissions and not GHG. Although evaluating GHG emissions is of extreme importance to asses the potential for emission reductions, this is not an objective of this work. Moreover, comparison of CO2 is a good proxy for energy related emissions, since this is clearly the main source of energy related GHG emissions (accounts for roughly 97% of GHG of the energy sector as stated in NIR – national inventory report - IA, 2006b).

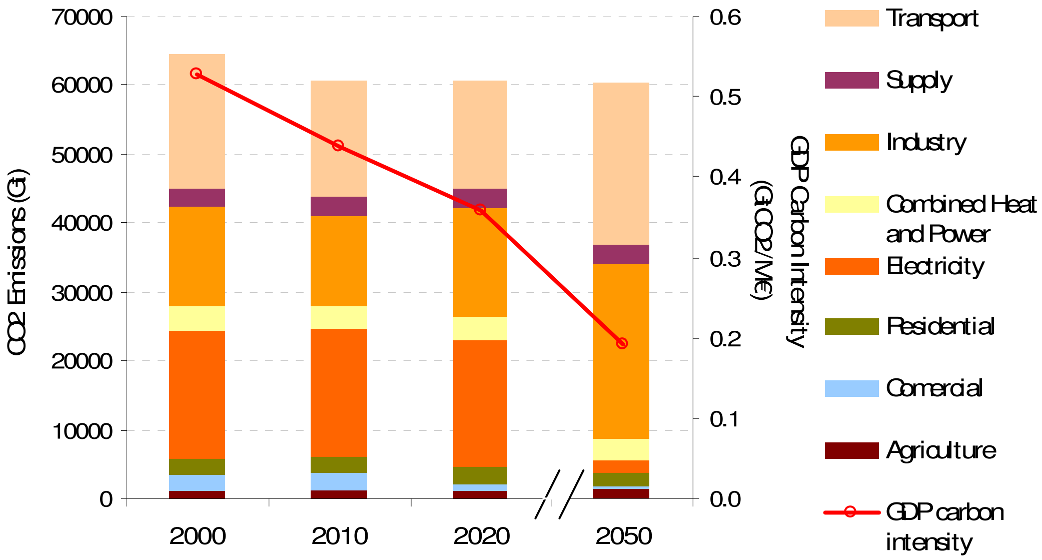

Figure 3.5 - CO_2 emissions by sector on the REF scenario and GDP carbon intensity

Energy related CO_2 emissions, presented in Figure 3.5, tend to reach a constant level from 2010 onwards and the reduction from 2000 to 2010 (6%) is strongly related to the transport sector. The fact that an obligation of 10% biofuels incorporation in diesel and gasoline is imposed, the switch between diesel and gasoline and the introduction of more efficient cars explains this behavior. From 2020 onwards emissions from the transport sector continues to rise driven by growth in demand. One should remind that transport demand projection for 2050 followed the past trend which is a rude estimation (for details see Annex I). However, this trend does not compromise the objectives of this work since transport sector was assumed not to have changes with climate change hence the comparison between scenarios is still valid.

One other important changing sector is the electricity production which roughly maintains emissions from 2000 to 2020 due to the introduction of large renewable capacity although electricity production is increased (see next section for further details). In 2050 emissions from this sector are dramatically reduced due the large penetration of renewable energy sources.

3.1.4. Electricity and heat sector

Installed electricity capacity and production per energy carrier

Results on this chapter relate to both centralized electricity and combined heat and power in order to have a clear picture of all the electricity production technologies. In Figure 3.6 the evolution of capacity installed by technology aggregated by fuel type can be observed. Table 3.2 shows the aggregation made.

Table 3.2 – Technology aggregation by fuel type (Ren – Renewable Energy Sourced Technology)

Aggregation	Fuels	Technologies
Ren - solar	Solar	Concentrated solar power
	Solar	Photovoltaic
Ren - Wind	Wind	Wind turbines
Ren – Others	Biogas; Black Liquors; Coke Oven Gas and Blast Furnace Gas (2000 only); Biomass; Refinery Gas; Geothermal; Industrial Waste	CHP
	Waves	Generical wave technology
	Municipal Waste	Steam turbines
	Wood	Steam turbines
Ren - Hydro	Hydro	Small and large hydro power plants: run-of-river or dam and pumped storage or not
Oil products	Heavy Fuel Oil	CHP - backpressure or condensing
	Heavy Fuel Oil	Steam turbines
Natural Gas	Natural Gas	CHP – backpressure or condensing
	Natural Gas	Combined cycle
	Natural Gas	Steam turbines
Coal	Coal	Steam turbines
Coal (CCS)	Coal	IGCC (integrated gasification combined cycle) with CCS

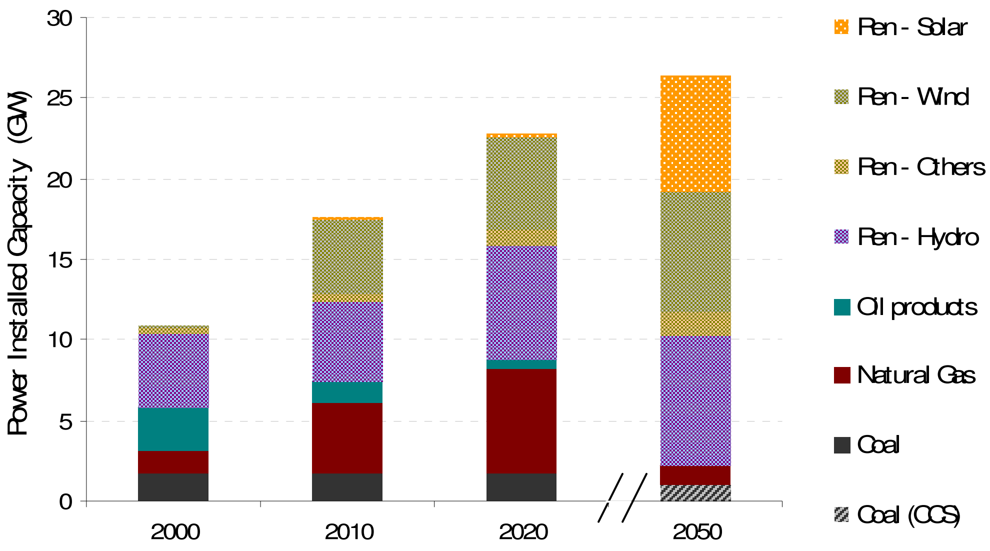

Figure 3.6 - Electricity installed capacity by technology aggregated by fuel type

Electrical installed capacity has an increasing behaviour (+61% in 2010 and +143% in 2050 in relation to 2000 values) following not only increased electricity production but also the fact that renewable energy sources with lower availability factor than fossil fuel plants strongly penetrate. The introduction of renewable energy sources implies a higher ratio between capacity installed and electricity produced, which means that, to produce more electricity the increase in installed capacity has to be higher than if it was driven only by fossil fuel plants.

The share of capacity from renewable energy based technologies increases from 46% in 2000 to 58% in 2010 and 92% in 2050. This increase is mainly due to already predicted increase in wind and hydro capacity but in 2050 a new technology appears preponderant in the profile: concentrated solar power[13] (CSP) which accounts for roughly 98% of the solar energy used. This technology starts slowly right after 2010, and stays with a small share of capacity until 2035, but sharply rises after that year following the decommissioning of conventional coal power plants and specially a

[13] More details on this technology can be found on DLR (German Aerospace Center) webpage (http://www.dlr.de/tt/med-csp) DLR, 2005.

large share of the natural gas combined cycle plants that reach the end of their lifetime.

As expected the impact of renewables in electricity production is lower when compared to installed capacity, although significant as it might be seen in Figure 3.7. It is also observed that coal power plants with carbon capture and sequestration are present in 2050 following their introduction in 2035 – this technology is IGCC (integrated gasification combined cycle)

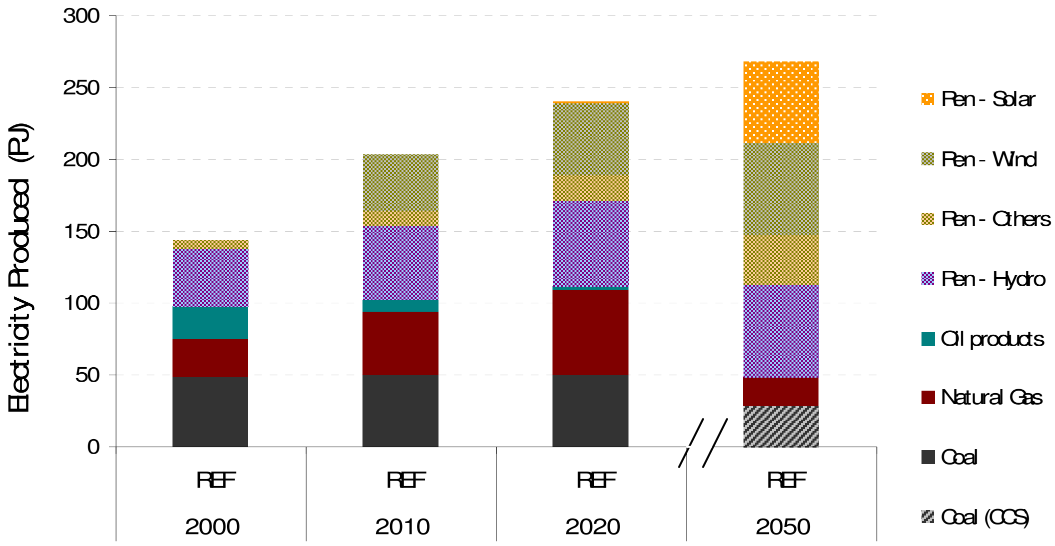

Figure 3.7 - Electricity production by technology aggregated by fuel type

The electricity production profile is quite similar to installed capacity except for the fact that renewables have a lower share: 33% in 2000 and 82% in 2050. Also increase in electricity production is much lower than increase in capacity: 41% in 2010 and 85% in 2050.

Renewable electricity - Zoom on hydropower

Hydro capacity installed is quite similar to the maximum possible installed capacity (see Figure 2.4) except for the fact that the generic hydropower plant is only introduced in 2030 when the model had the freedom to install it in 2025. Figure 3.8 and Figure 3.9 show the capacity and electricity production of the hydropower technologies. In fact generic hydropower was the only type of hydro technology that was left for the model to choose in the REF scenario since all others were forced to entry as defined for this scenario.

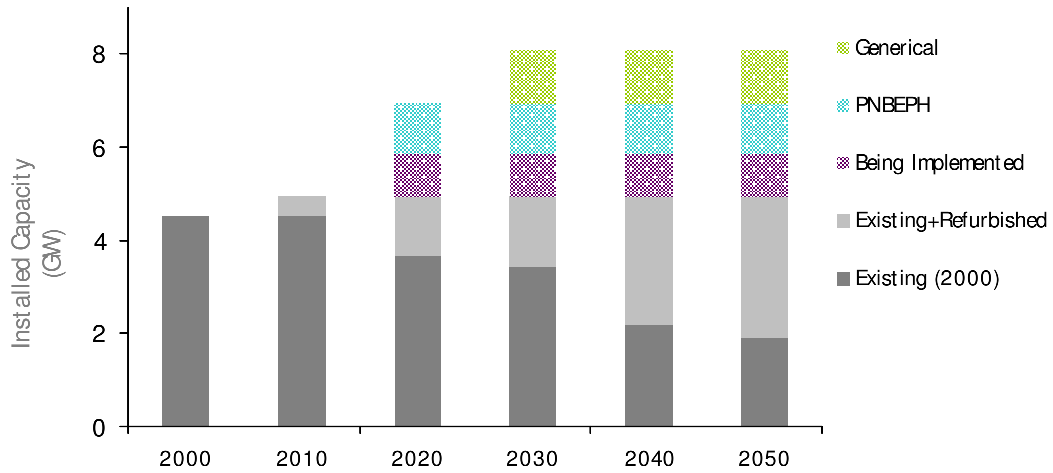

Figure 3.8 - Electrical installed capacity of hydropower plants in the REF scenario

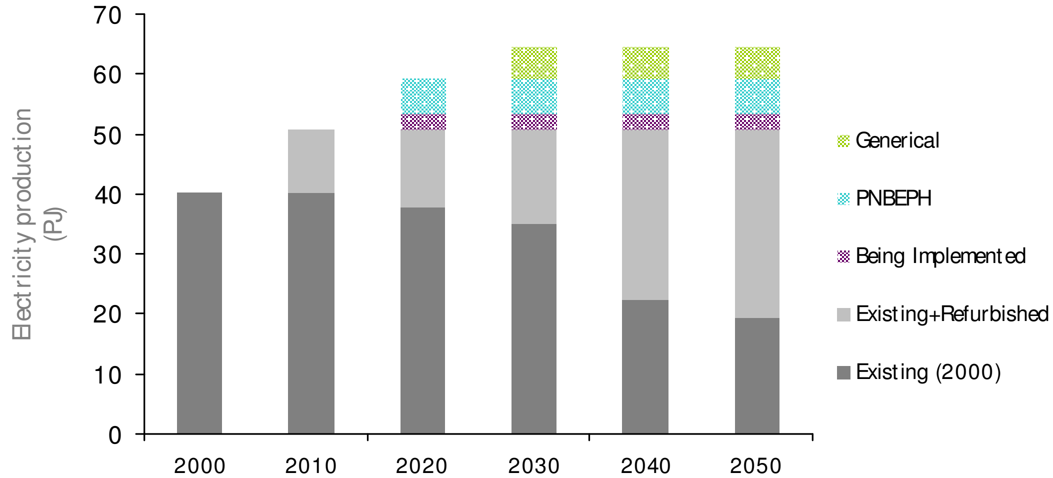

Figure 3.9 - Electricity production from hydropower plants in the REF scenario

One important result refers to the facts that increased total installed capacity beyond 2010, i.e. due to new hydropower plants, was of 63% whereas electricity production from this source only increased 27%. This means that most of the high productivity sites have already been built and new hydropower plants will have significantly less electricity output per unit of installed capacity.

3.2. Climate Change Scenarios

Results presented in this chapter, relate the REF scenario with the four climate change scenarios studied: Low and High, respectively low impact of climate change and high impact of climate change and the same scenarios but without the obligation to install the new hydropower investments.

For an easier comparison, results for the REF scenario will be presented on each figure. Also for an easy reading only three years will be presented: 2000 (only REF scenario), 2020 intermediate year (yet close enough to allow empirical validation of results) and 2050, the latest year of the analysis.

3.2.1. Primary energy supply and final energy consumption

Primary energy presents no major changes within scenarios, but still some differences occur as illustrated in Figure 3.10.

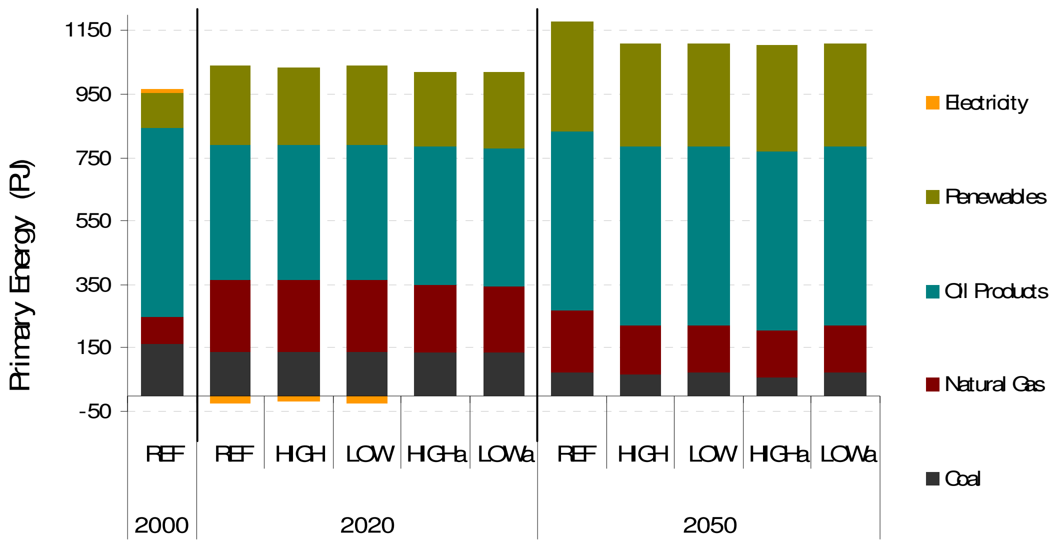

Figure 3.10 - Primary energy supply for the five scenarios analysed in 2000, 2020 and 2050

In 2020, climate change impacts are still minor since it was assumed that only after this date demand should start to suffer from climate change impacts. Even so, it is possible to observe the impact of forcing the introduction of the projected hydropower plants. In fact, in 2020 on the HIGHa and LOWa scenarios there is little net electricity export which means that electricity production for these scenarios is no longer exceeding internal demand.

In 2050, effects of the climate change on demand for residential and commercial sector are visible with reducing primary energy supply on the scenarios with climate change (a reduction of 6% relative to the REF scenario in 2050). Even so, this decrease is approximately the same for all scenarios which means that higher or lower impacts of climate change have the same result in primary energy supply. The remaining results should clarify if there are other differential impacts throughout the energy system.

From the analysis of the primary energy consumption it is not clear if the obligation of introducing the projected hydro investments has a strong impact on the energy system since results from the LOWa and HIGHa scenarios are quite similar to LOW and HIGH, mainly for 2050.

Final energy demand as presented in Figure 3.11, supports the early conclusion that allowing the model to choose the hydropower capacity, in particular has an influence on the amount of excess electricity generated.

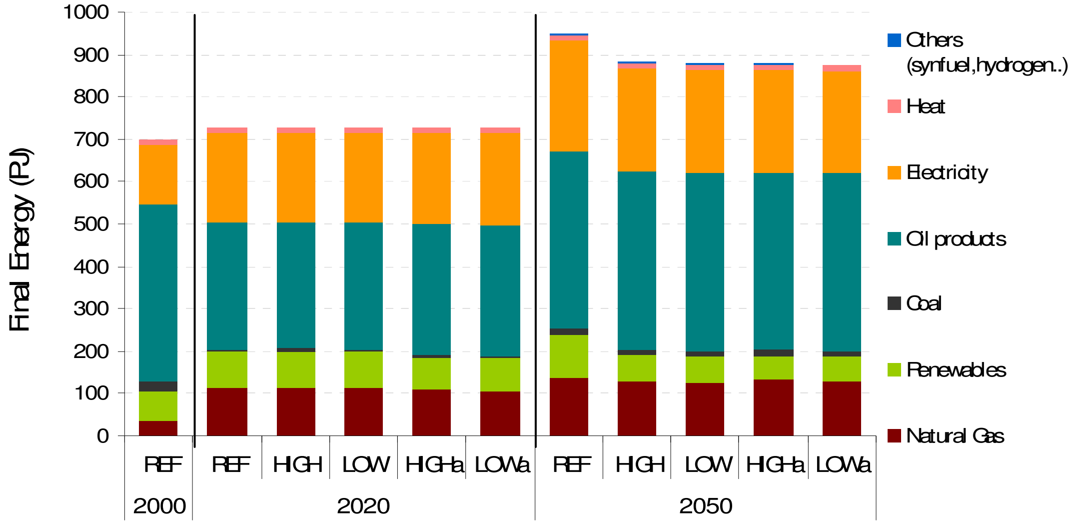

Figure 3.11 - Final energy consumption for the five scenarios analyzed in 2000, 2020 and 2050

Since final energy results are quite similar between all scenarios in 2020, it confirms that the difference seen in primary energy for this year relates to electricity production. Detailed analysis of this sector (see 3.2.4) will provide a deeper insight on the sector.

As in primary energy, the impact of climate change is visible in 2050 with a reduction of about 8% in final energy when compared with the REF scenario. Reduction of renewables from the REF scenario to the remaining scenarios in 2050 should be underlined. This is due to for two reasons: on the one hand, reduction of global demand on the residential and commercial sectors implying that renewables have “less market” to penetrate, as explained on the next section; on the other hand, and far more important, as will be thoroughly described in the detailed analysis of the electricity sector, there is a shift from biomass that was used as final energy in residential to CHP production.

3.2.2. Final energy consumption in commercial and residential sectors

As mentioned previously, results indicate that renewable penetration in the commercial and residential sectors are lower in the climate change scenarios, as can be seen on Figure 3.12 and Figure 3.13.

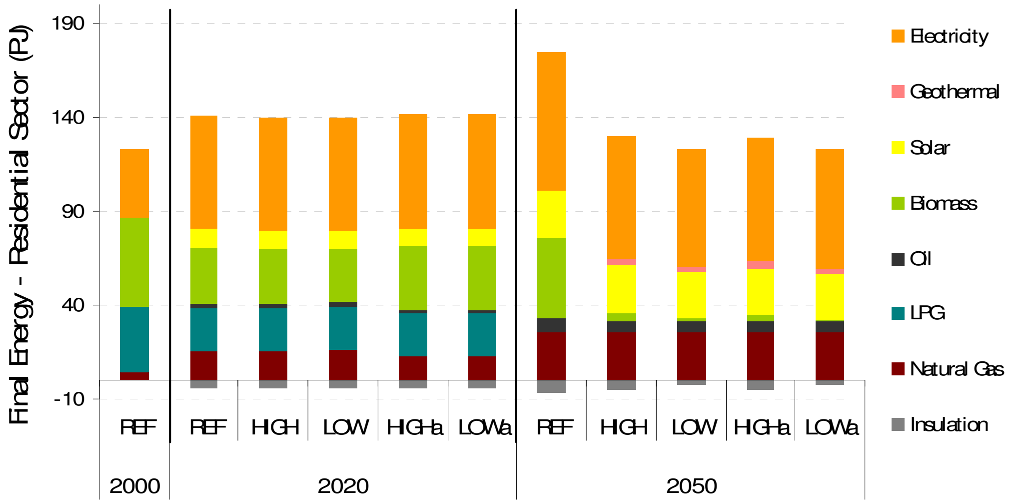

Figure 3.12 - Final energy consumption for the five scenarios analysed in 2000, 2020 and 2050 in the residential sector

Final energy consumption in residential sector is quite uniform among scenarios, in 2020. There is only a slight increase on the use of biomass on the HIGHa and LOWa scenarios taking the place of natural gas.

In 2050, differences are much more evident, with a strong reduction in energy consumption (-26% in both HIGH scenarios and -30% in both LOW scenarios) It should be reminded that, although counter-intuitive, LOW scenario has higher reduction of heating demand in the residential as it was explained in 2.4.2. As already stated, as final energy consumption decrease, following useful energy demand reduction, renewable penetration is much lower due to lack of market space penetration: the share of renewables reduces from 39% in the REF scenarios to 23 and 26% in the remaining scenarios. The same reasoning applies for insulation, although it appears evident in LOW and LOW a scenarios (decrease of 60% relative to REF scenario), where demand is lower.

The remaining fuels don't seem to be affected in terms of share in the profile as they configure a base consumption due to the lower price or convenience of use as in the case of electricity. Nevertheless, the reduction of total final energy demand in the HIGH scenarios implies a reduction of final energy consumption – the model decides to reduce the consumption of the most expensive technologies and fuels which means, in this case, the reduction of geothermal energy use and insulation.

The analysis of the results of the commercial sector (Figure 3.13) derive similar conclusions as for the residential sector with, in this case, the HIGH scenario implying a higher reduction of demand as seen on 2.4.2.

In 2050, HIGH and HIGHa scenarios face a reduction of 21% from the REF scenario and LOW and LOWa a reduction of 18% in total final energy. The share of renewables goes down from 14% in the REF scenario for about 7% in the climate change scenarios.

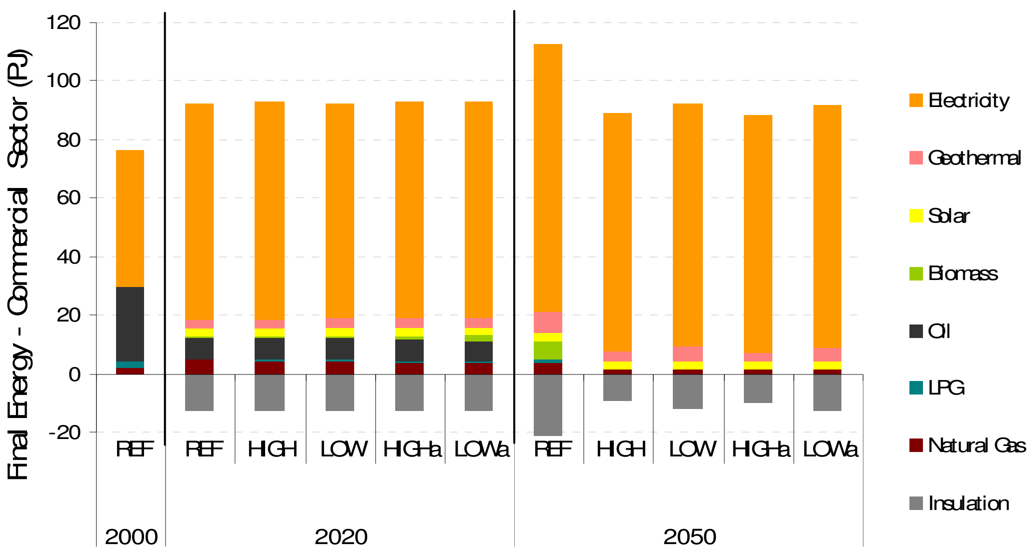

Figure 3.13 - Final energy consumption for the five scenarios analyzed in 2000, 2020 and 2050 in the commercial sector

3.2.3. CO_2 emissions

Analysis of global CO_2 emissions (Figure 3.14) does not show significant differences between scenarios, the only exception being the reduction of emissions from CHP as biomass takes its place in this sector that will be analyzed in the next section. Also residential and commercial sector reduce their emissions in 2050 in the climate change scenarios following the reduction of demand as it was already envisaged from fuel consumption. This variation is meaningless on total CO_2 emissions (less than 1% of total CO_2 emissions although emissions reduction from residential sector account for 12% of total emissions reduction). Total CO_2 emissions decrease 5% in 2050 for the scenarios with climate change in relation to the REF scenario.

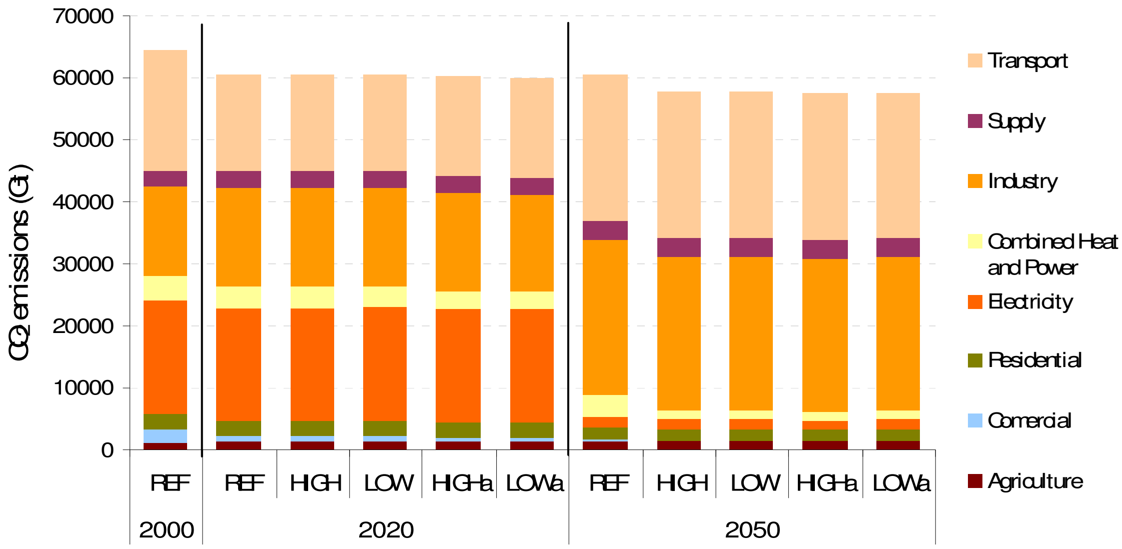

Figure 3.14 - CO_2 emissions of the scenarios analyzed in 2000, 2020 and 2050 by sector

3.2.4. Electricity and heat sector

Installed electricity capacity and production per energy carrier

Electricity and heat production is the sector where both climate change impacts and the forcing hydro capacity are most directly observed. Figure 3.15 reveals clearly the first results about impacts on investment decisions on hydropower capacity. Looking at 2020, for the HIGHa and LOWa scenarios, it is clear that the model, with no obligation to accomodate, decided to invest far less in new capacity; total hydro capacity is on average 20% (22% on HIGHa and 18% on LOWa) less in the free scenarios than in the forced hydro scenarios.

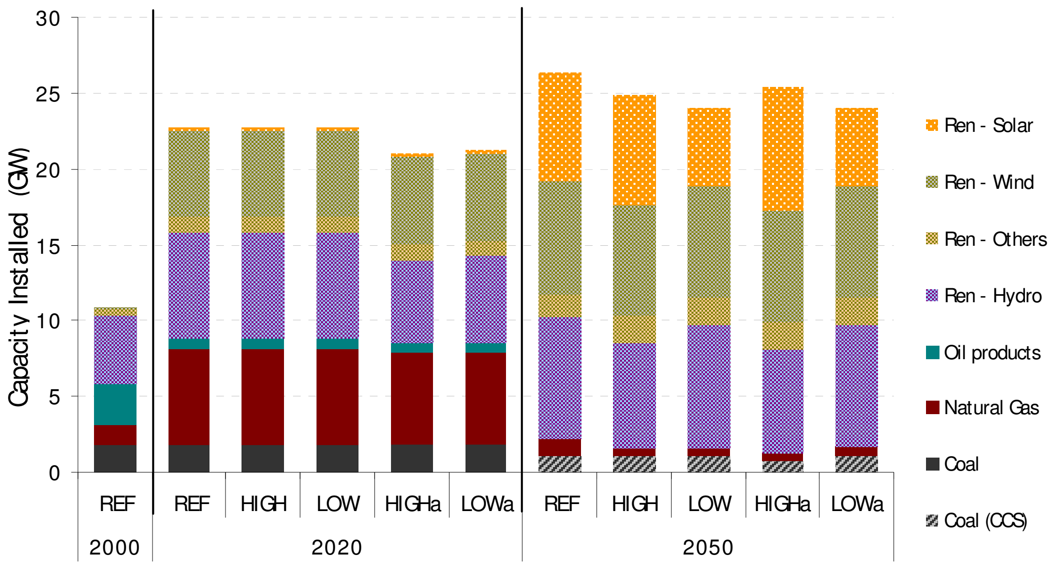

Figure 3.15 - Electricity installed capacity by technology aggregated by fuel type for the scenarios analyzed in 2000, 2020 and 2050

In 2050, all the climate change scenarios show a reduction of installed capacity in comparison with the REF scenario (-4 to -9%), with the highest difference in the LOW scenarios. Although electricity production is roughly the same (see Figure 3.16) from climate change scenarios, in the LOW scenarios hydro has a higher availability factor (see Table 2.4 on page 24) therefore it is able to produce more electricity for each capacity unit. This explains the lower installed capacity on these scenarios.

Also in 2050, hydro capacity is lower in HIGH scenarios (-14% on the HIGH and -16% on the HIGHa) relative to the remaining scenarios. This indicates that, given lower availability factors, hydro becomes less competitive and is clearly substituted with CSP solar plants.

It is also possible to observe, in 2050, that CCS coal power plants have less installed capacity in the HIGHa scenario (-30% than in the remaining scenarios). In fact in the free scenarios (HIGHa and LOWa) due to the lower installed capacity of hydro in the mid years of the time horizon, CCS comes into place earlier (2025 when in the other scenarios is only present in 2035). In the HIGHa scenario the installed capacity of CCS in 2025 is the highest. Since this technology has a lifetime of 25 years in 2050 the model chooses to substitute the plants installed in 2025 with a little extra CSP solar panels capacity. This indicates that early forcing of hydro capacity above optimum level, can delay the penetration of alternative technologies such as CCS and CSP. For further details, see Annex II for supply curves of these technologies.

The lower electricity demand on the climate change scenarios implies that natural gas capacity is decommissioned earlier: in fact, climate change scenarios have a reduction of 50% in relation to the REF scenario.

It is important to mention that, even tough HIGH scenarios have less hydro capacity, in 2050 all scenarios point to a full implementation of PNBEPH as can be seen below (*zoom on hydropower* section).

Electricity production, as presented on Figure 3.16 does not reveal much extra information except for the fact that in 2020 it is already possible to infer that lower availability factors on hydro start to make a difference on electricity output. Both HIGH scenarios have lower electricity output from hydro (approximately 7% lower) when compared with the respective LOW scenario.

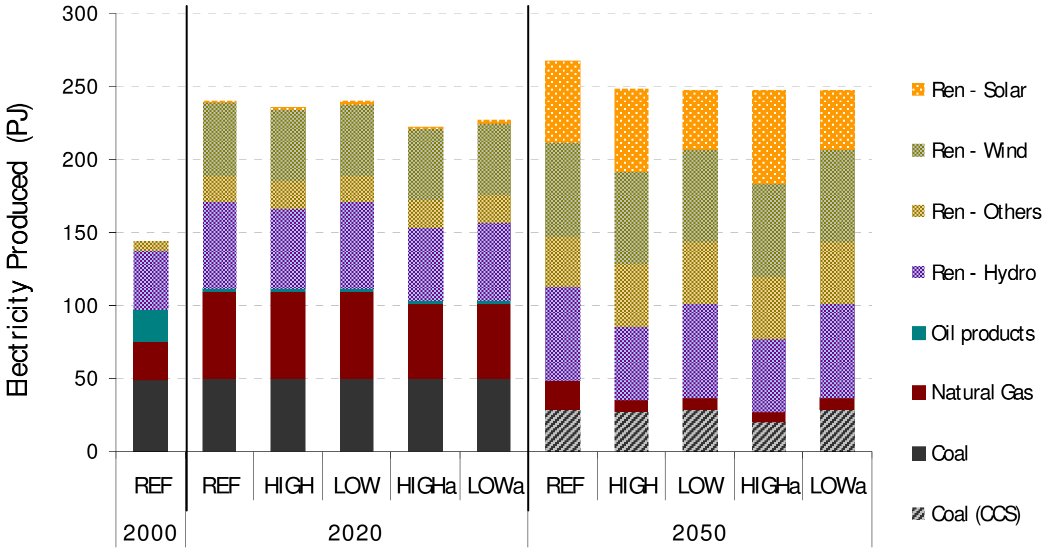

Figure 3.16 - Electricity produced by technology aggregated by fuel type for the scenarios analyzed in 2000, 2020 and 2050

Zoom on CHP

On the analysis of final energy consumption (3.2.1) it was referred that CHP might suffer some changes due to the reconfiguration of the energy sector. Some results of this sector will therefore be presented, as seen on Figure 3.17.

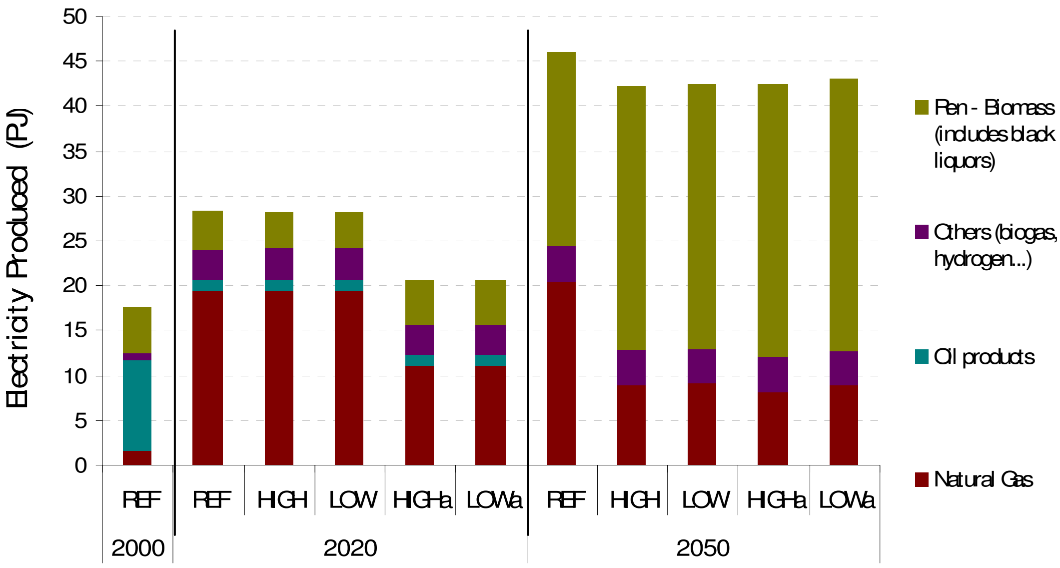

Figure 3.17 - Electricity produced in CHP by technology aggregated by fuel type for the scenarios analyzed in 2000, 2020 and 2050

In 2020, it is interesting to see that decision on investments in hydropower strongly influence CHP electricity production, by reducing its output (27% lower in HIGHa and LOWa scenarios compared to the remaining scenarios) when hydropower is also lower. This is somewhat another counter-intuitive result since it could be expected that CHP could somewhat compensate the lower installed capacity of hydropower. In fact, the higher investment costs associated with forced new hydropower plants rise slightly the electricity price of the system in 2020 (see 3.2.5) therefore making CHP more competitive when electricity prices are higher, as occurred in REF, HIGH and LOW scenarios.

In 2050, despite a small decrease in electricity output in CHP (-5%) in climate change scenarios the most important difference refers to 39% increase of biomass relative to REF scenario. As a result of the decreasing demand in the residential sector for these scenarios, biomass becomes available to be used on another part of the system which is directed to the CHP sector replacing natural gas. Endogenous biomass has a lower cost than imported one (see section 2.1.4), which means that, in the scenarios analyzed, biomass imports are not competitive and endogenous biomass stock is a cheap option to be used in the most cost-effective sector (the most cost-effective sector varies according to the scenarios).

This means that CHP sector is able to reduce its CO_2 emissions on climate change scenarios, not only by reducing electricity output but most importantly by replacing gas with biomass.

Seasonal change of electricity generation

Since the electricity demand on sectors (residential and commercial) for which a seasonal and daily load curve exists was changed (for instance stronger needs for cooling and lower needs for heating change the seasonal load curve), it is important to look at electricity production in the different seasons to check the impact of climate change inter-annually; the year 2050 was chosen for the analysis.

Figure 3.18 shows that seasonal load electricity production has a strong variation between the REF scenario and scenarios with climate change impacts although, among these, differences are very small.

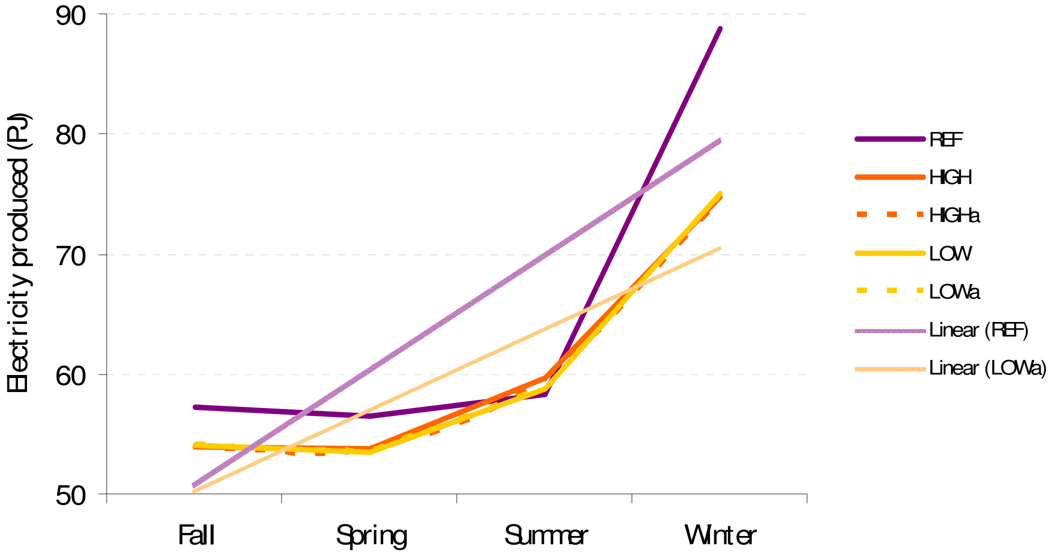

Figure 3.18 - Seasonal production of electricity and respective trendlines

As expected due to the lower heating demand and higher cooling demand, electricity production goes down in fall, spring (-5 to -6%) and winter (-15% to -16%) and slightly up on summer (1 to 2%) on the climate change scenarios.

These variations show another interesting impact of climate change. Looking at the linear trendlines of the REF scenario and from the climate change scenarios, it is possible to observe a flattening of the annual load curve which could mean the need for less reserve capacity on peak periods.

Renewable electricity – zoom on hydropower

From Figure 3.19 it is clear that, in 2050, different climate change scenarios strongly affect optimal hydro capacity to be installed.

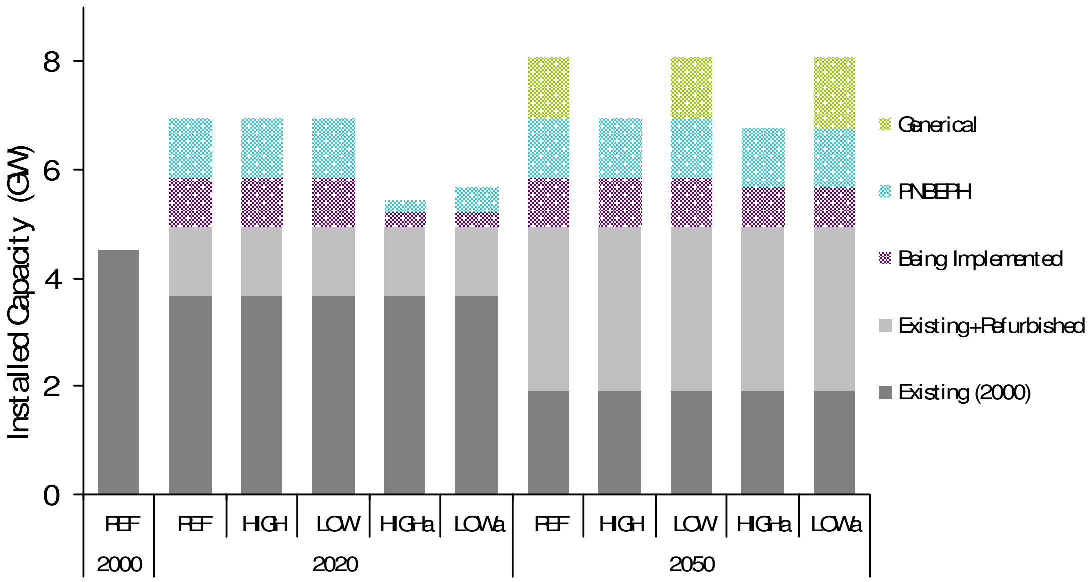

Figure 3.19 - Electrical installed capacity of hydropower plants for the five scenarios analyzed in 2000,2020 and 2050.

In the year 2020, results strongly suggest that current policy objectives on hydropower are overestimated both in what regards the projects being implemented and dams from PNBEPH. New capacity installed in LOWa scenario is 64% lower than in the scenarios where hydro capacity is forced to entry. In the HIGHa scenario this difference is even higher: -75%. Between LOWa and HIGHa the only difference is that, due to more favorable availability factors on LOWa, investment on PNBEPH is higher. In this case Foz Tua dam is installed earlier.

In the HIGH scenarios, for 2050, installed capacity is -15% than in the remaining scenarios. The lower availability factors on the HIGH scenarios make the "generical" hydropower plants non-competitive and this is the most important difference between the scenarios. All the plants from PNBEPH are fully installed in 2050 as they are still competitive even in the HIGH scenarios. The only remaining difference is the projects being implemented that are slightly lower when the model is left to choose the capacity to be installed (HIGHa and LOWa). This happens because under these scenarios the Baixo Sabor dam is never chosen by the model. Details on each plant installed by scenario can be found on Table 3.3.

Electricity production profile will not be showed since it projects the same conclusions already mentioned except for the fact that electricity production is lower by unit of capacity, as expected, in the same proportion of the availability factor reduction (see 2.4.1)

Table 3.3 – New hydropower plants installed capacity (GW) by scenario and year

Aggregation		2020					2050				
		REF	HIGH	LOW	HIGHa	LOWa	REF	HIGH	LOW	HIGHa	LOWa
Being implemented	Alqueva II	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
	Baixo Sabor	0.17	0.17	0.17	N/I	N/I	0.17	0.17	0.17	N/I	N/I
	Bemposta II	0.18	0.18	0.18	N/I	N/I	0.18	0.18	0.18	0.18	0.18
	Picote II	0.23	0.23	0.23	N/I	N/I	0.23	0.23	0.23	0.23	0.23
	Ribeiradio	0.07	0.07	0.07	N/I	N/I	0.07	0.07	0.07	0.07	0.07
PNBEPH	Alvito	0.05	0.05	0.05	N/I	N/I	0.05	0.05	0.05	0.05	0.05
	Daivões	0.11	0.11	0.11	N/I	N/I	0.11	0.11	0.11	0.11	0.11
	Foz Tua	0.23	0.23	0.23	N/I	0.23	0.23	0.23	0.23	0.23	0.23
	Fridão	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
	Girabolhos	0.07	0.07	0.07	N/I	N/I	0.07	0.07	0.07	0.07	0.07
	Gouvães	0.11	0.11	0.11	N/I	N/I	0.11	0.11	0.11	0.11	0.11
	Padroselos	0.11	0.11	0.11	N/I	N/I	0.11	0.11	0.11	0.11	0.11
	Pinhosão	0.08	0.08	0.08	N/I	N/I	0.08	0.08	0.08	0.08	0.08
	Vidago	0.09	0.09	0.09	N/I	N/I	0.09	0.09	0.09	0.09	0.09
	Almourol	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Generical	Generical	N/I	N/I	N/I	N/I	N/I	1.12	N/I	1.12	N/I	1.30

Unit: GW
N/I = Not Installed

3.2.5. Electricity price evolution and system costs analysis

The evolution of electricity price is a good indicator of the impact of different electricity production profiles. Electricity price presented is the shadow price determined by the model for this commodity and refers to price on production, i.e., without distribution costs. For this purpose, 2005 values will be presented as a reference, instead of 2000 as in previous analysis. The 2000 prices are extremely high and are not representative, because in 2000 capacity for electricity production was strictly fixed to match exactly the capacity installed in this year. This means that electricity production is very near the limits of capacity which creates for that year a high shadow price associated with the scarcity of the commodity. This highly constrained configuration is only true in the base year since from that year onwards the model has the possibility to install extra capacity if needed.

As can be seen on Table 3.4, production electricity price is not strongly influenced between scenarios although significant changes occur throughout the time horizon. The only difference is the confirmation of the already mentioned lower price of electricity (-11% comparing to remaining scenarios) in 2020 for the LOWa and HIGHa scenarios as a result of lower investments costs on hydropower.

Table 3.4 – Electricity price evolution

	REF	HIGH	LOW	HIGHa	LOWa
2005	5.10	5.10	5.10	5.10	5.10
2020	3.96	3.96	3.96	3.52	3.52
2050	6.50	6.52	6.52	6.51	6.51

Unit: €cents/kWh

In 2005, electricity price is higher than in 2020, since in that year hydro production was much lower than an average year due to the extreme drought[14]. There was a strong use of heavy fuel oil in that year which caused the production costs to increase significantly. Also in 2020 there is a strong increase on installed capacity driven both by direct growth in electricity demand but also by forced installed capacity (especially renewables such as wind) which means electricity becomes abundant and therefore price is lower.

In 2050, despite the differences in installed capacity and profile between scenarios the price is very similar. This means that, for instance hydro and CSP, are perfect substitutes and under different shares of these two technologies the price is unaltered. The strong change in electricity production profile with the strong penetration of renewables and advanced technologies implies an increase in electricity price: in fact from 2020 to 2050 the price increases 65%.

As part of the objective function, TIMES calculates total discounted system costs[15] ($€_{2000}$) which provides data for scenario comparison. Although absolute total system cost refers to the total accumulated cost of the energy system from 2000 to 2050, thus with a limited interest to interpret, the differences of this cost between scenarios provides valuable information on cost-effective options.

From Figure 3.20, it is clear that all climate change scenarios have lower costs than the REF scenario. This is an expected result, since demand is lower and by consequence, also the power installed capacity, which has strong impacts on overall system costs. The LOW and HIGH scenarios allow total savings of approximately 45000 $M€_{2000}$ and 6100$M€_{2000}$ when compared to the REF scenario.

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[14] Hydro Productivity Index (HPI) was 0.34 in 2005 when, in an average year should be around 1 (DGEG, 2008a)

[15] TIMES_PT uses a discount rate of 4%, undifferentiated between sectors.

Figure 3.20 - Total system costs variations, compared to the REF scenario

The scenarios where hydro capacity option is left free (HIGHa and LOWa) have the lower system costs. In fact comparing each climate change scenario (HIGHa and LOWa) with respective forced hydro scenario (HIGH and LOW) it is possible to observe that delaying the investment on hydropower results in a saving of approximately 2000 M€$_{2000}$ on the whole time horizon.

Investment costs allows for a screening of costs throughout the time horizon. Yearly investment costs of the electricity and heat production sector (centralized electricity and CHP) are plotted on Figure 3.21. It should be noted that investment costs are annualized through each technology lifetime and costs presented show annual capital costs associated.

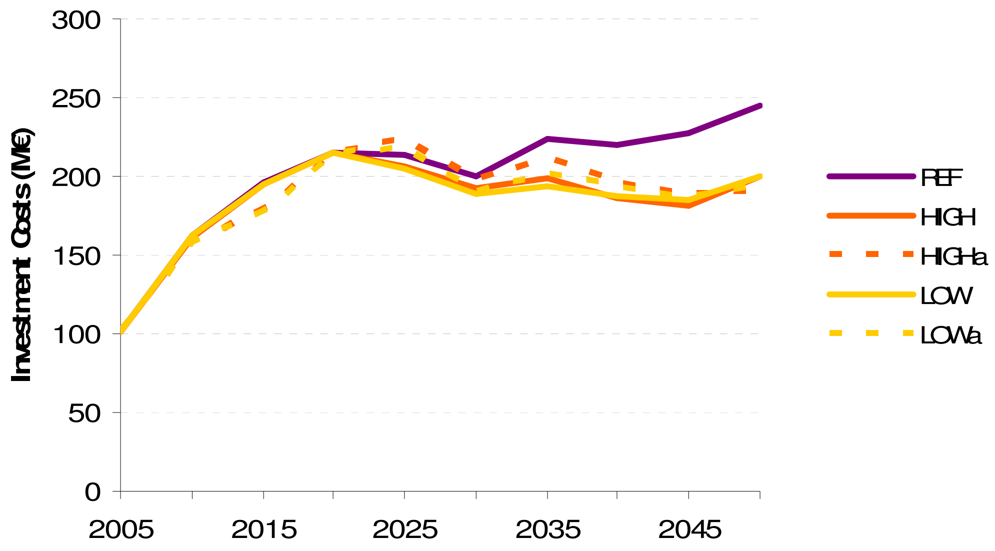

Figure 3.21 - Yearly investment costs for the electricity and heat sectors

It can be seen that the REF scenario shows the highest investment costs for most of the years except for 2025 where HIGHa and LOWa scenarios have slightly higher investment costs. Until 2025, the higher investment costs are associated with hydropower capacity installed and in the remaining years with the higher demand in the REF scenario.

HIGHa and LOWa scenarios present lower investment costs until 2020 and higher from then on, which shows that, from a cost effective approach, it is better to delay the investment on hydropower. On the year 2050 investment costs of these scenarios are lower since the earlier investment on CSP implies less capacity installed in the later period.

Comparing the HIGH and LOW scenarios with the respective HIGHa and LOWa scenarios, both HIGH scenarios show higher investment costs since investment on CSP is higher to compensate low availability factor of hydropower.

4. Conclusions

The main objectives of this thesis were the assessment of the impacts on the Portuguese energy system due to climate change induced and to evaluate effectiveness of currently planned hydropower capacity, since there is still little literature and quantified evaluation of interactions between mitigation, adaptation strategies and climate change impacts. Both the objectives were accomplished and an important contribute was made in quantifying interactions between climate change impacts and mitigation strategies.

The work presented shows that climate change has a very important impact on the energy sector especially in hydropower profile – lower availability of water seriously compromises hydropower investment and electricity production from this source - and on demand – increases in temperature lead to an overall reduction of demand for useful energy.

The main outcomes also reflect that previously works done on the evaluation of these impacts (namely the analysis done on SIAM) have proven to be insufficient and lead to contradictory results. The insufficiency comes from the fact that, as it has also been referred on SIAM, it has not been possible to evaluate the interactions between all these impacts until now. This work contributes to overcome this gap. The TIMES optimization model is a tool that allowed an integrated perspective of the problem. In fact, the results presented show that evaluating impacts in an integrated manner can lead to significantly improved results. It should be reminded that SIAM concluded that overall demand should increase due to increasing demand for cooling and that impacts on hydropower could be meaningless. It has been shown that both conclusions can be highly disputed when evaluated under the framework defined for the evaluation presented on this thesis.

Overall, the innovation from the present analysis refers to the tool used, with capabilities of evaluating full impacts and interactions between sectors that lead to substantially different conclusions than strictly from a sector by sector analysis.

One example of this is the lower share of renewables on final energy consumption on residential and commercial for the scenarios with climate change when compared with the REF scenario (39% in the REF scenarios and between 23 and 26% in the remaining scenarios), even though total CO2 emissions remain lower on the climate change scenarios. This result suggests that renewable penetration targets can be misleading since reductions in energy demand have a larger impact on the reduction of CO2 emissions. Lower energy demand means lower share of renewables but also lower emissions hence there is an urgent need to evaluate the benefits of introducing more renewables vis-à-vis a reduction of demand. It should be stressed out that these results are strongly influenced by existing and predicted configuration of national energy system and results suggest a strong debate on policy objectives but conclusions are strictly applied to the Portuguese energy system.

The results obtained with significantly lower levels of emissions and lower costs on the climate change scenarios suggest that non-technical measures aiming demand reductions (such as city tolls or incentives to reduce the number of hours with heating) might have a strong potential on complying carbon reduction objectives. This was not an objective of this work but a side result that indicates further investigation on these measures and their impacts is essential.

It has also been thoroughly demonstrated that delaying investment on hydropower capacity is a cheaper option that maintains exactly the same level of emissions with the side effect of reducing electricity net exports. In association with this, the high uncertainty of demand projection beyond 2020 strongly suggests that it is wise to delay the introduction of massive hydropower plants. In the future energy demand projection can be updated with new envisaged trends and the decision of installing new hydropower plants can be made with much more certainty. It should be reminded that the scenarios studied do not take into account possible market strategies to export electricity, instead it evaluates what is the cost effective option to provide internal demand of electricity.

From all the hydropower projected investments included in PNBEPH the tool used suggests that, by 2020, from a strict cost-effective analysis point of view only Fridão and Almourol dams should be built. The ecological gains are also obvious since hydropower has strong impacts on biodiversity and land use as demonstrated on PNBEPH environmental impact assessment. Another important point is that delaying investment on hydropower benefits the early introduction of alternative technologies such as coal IGCC power plants with CCS and concentrated solar power.

The analysis of the electricity production sector revealed CSP as a promising technology for the future. The situation could be even more favourable if the envisaged deployment of storage technology (DLR, 2005) is capable of approaching CSP availability factor from fossil fuel plants contributing to base load demand. Another result on the electricity sector was the growing penetration of renewable electricity (reaching more than 80% of the electricity produced in 2050). This could raise some questions on security of supply but no lower limit was set on fossil fuel plants since technological development might overcome the fact, that for now, renewable energy sources are not fully reliable. One example of this is the already mentioned thermal storage for CSP that might induce an availability factor near 90%. It should also be mentioned that drought or extremely wet years were not modelled, hence the results for 2050, indicate the behaviour of the system under average hydrological years.

Although the magnitude of climate change might induce different electricity technology penetration (hydropower can be reduced on higher impacts scenarios), overall climate change has positive effects on the energy system both on energy related costs and emissions, by means of energy demand reduction. Also the flattening of the annual load curve might have ancillary benefits on the electricity production sector since it reduces the buffer needed for reserve capacity.

One of the most critical handicaps of this work refers to the high uncertainty behind energy demand projection. Although for 2020 the trend has been validated under other frameworks (MAOTDR, 2008) from then on the extrapolation made is a rough estimate with the sole objective of allowing evaluation of impacts in 2050 where climate change impacts should be quite noticeable. This is especially true for the commercial and residential sector. Even so base demand used in the present work here, reflects the extrapolation of trends from 2020-2030; having in mind that in the future behavioural change (driven not only by higher energy prices but also by increasing social awareness) could drive the growth trend to slow down, the base demand projected might be overestimated. This means that given the same demand reduction due to climate change on top of the base demand, the useful energy needs might even be lower which strengthens the conclusions presented.

Although reduction in water availability was validated having in mind future conflicts on the use of water, for the purpose of this work, no direct assessment was made regarding this specific subject. If climate change has a strong impact on hydro resources other uses such as agriculture will also increase water consumption leaving even less water available for electricity production. Also the work done does not account for basin-scale which could lead to cascade effects between water basins and also how the changes in the magnitude of precipitation events, drought periods, and links with Iberian Peninsula water basins could impact the availability of water on these scales. This means that extreme events (more days with heat waves for instance) are also not present on the configuration of demand with climate change.

No assessment was also done in linking co-benefits of hydro and wind energy. In fact, although hydropower has in the technological database differential availability factors throughout the seasons this is not the case for wind since electricity production from this source is not fully correlated with yearly seasons. This means the model can, to some extent (for example, it is not possible to use all the installed capacity in any timeslice), drive electricity production on the days and periods where it is the most needed ignoring the fact that sometimes wind could not be available.

Another possible impact of climate change not addressed in this work are the changes in crop yield potential and forest with consequent reduction or increase of primary energy potential for biofuels and biomass.

The main limitations referred above should be further addressed in future developments and new research directions should be fully analyzed (such as non-technical measures or evaluation of renewable energy policies).

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A. Annex I

Energy and Materials Demand

Projection

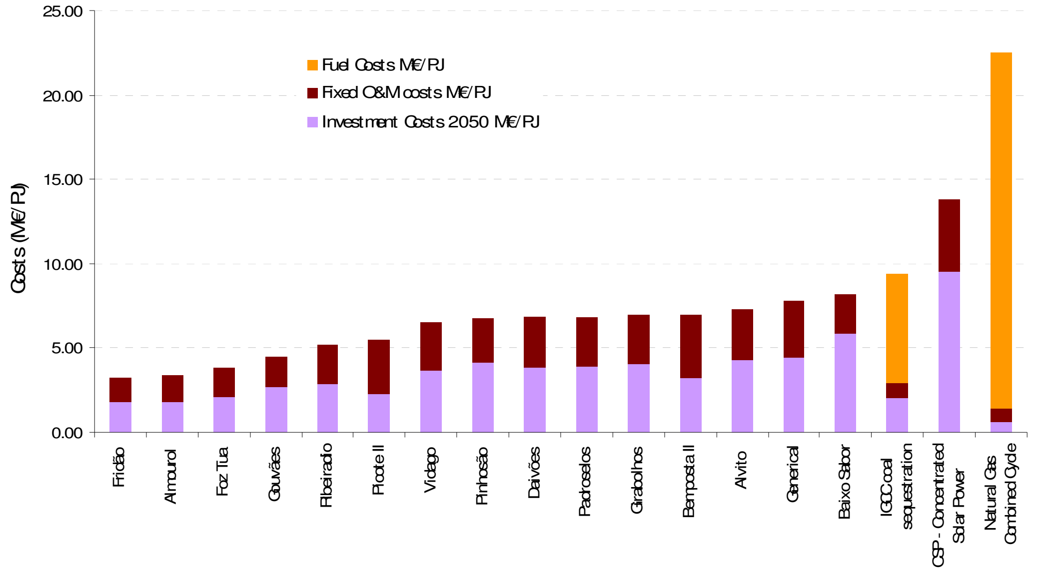
Annex I table 1 – Final Energy and materials demand (2000 – 2050)

Final energy and material demand category	Unit	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Agriculture	PJ	19.5	19.1	20.1	20.4	20.7	21.0	21.3	21.3	21.3	21.3	21.3
Ammonia Demand	PJ	0.3	0.3	0.3	0.4	0.4	0.5	0.6	0.6	0.7	0.9	1.0
Aviation Generic.	PJ	18.7	5.4	6.6	7.6	8.9	9.7	10.8	11.8	12.8	13.8	14.8
Cement Demand	Mt	10.1	9.9	10.4	11.6	12.5	13.3	14.2	15.2	16.3	17.4	18.6
Chlorine Demand	Mt	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.4
Comercial Cooking	PJ	1.0	0.8	1.3	1.5	1.7	2.0	2.3	2.6	3.0	3.4	4.0
Comercial Lighting	PJ	29.8	30.4	32.4	34.7	37.2	39.9	42.7	45.4	48.4	51.5	54.8
Comercial Other Electric	PJ	15.9	17.0	19.8	23.2	27.6	31.1	33.2	35.3	37.7	40.1	42.7
Comercial Public Lighting	PJ	3.9	5.1	5.6	6.4	7.3	8.3	9.4	10.6	12.0	13.6	15.4
Comercial Refrigeration	PJ	0.6	1.0	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Comercial Other	PJ	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Glass Flat Demand	Mt	0.1	0.1	0.2	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4
Glass Hollow Demand	Mt	0.9	1.0	1.2	1.4	1.5	1.6	1.7	1.9	2.0	2.2	2.3
High Quality Paper Demand	Mt	1.4	1.4	2.0	2.3	2.5	2.8	3.0	3.4	3.7	4.1	4.5
Iron and Steel Demand	Mt	1.0	3.7	4.1	4.6	5.2	5.8	6.6	6.7	6.8	6.9	7.0
Lime Demand	Mt	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.6
Low Quality Paper Demand	Mt	0.8	0.8	0.8	0.9	0.9	1.0	1.1	1.2	1.2	1.3	1.4
Navigation	PJ	3.2	3.6	3.8	4.1	4.4	4.7	5.0	5.3	5.6	5.9	6.2
Non Energy Consumption - Chemicals	PJ	72.2	65.5	68.2	72.3	76.3	79.7	83.8	88.6	93.7	99.2	105.2
Non Energy Consumption - Others	PJ	21.4	20.1	20.7	21.4	22.2	23.0	23.8	24.8	25.8	26.9	28.0
Other Chemicals Demand	PJ	21.7	19.9	22.4	26.3	28.8	31.2	34.1	37.4	41.1	45.1	49.7
Other Industries	PJ	68.1	58.3	57.5	57.9	59.3	60.5	61.9	63.5	65.1	66.8	68.6
Other Non Ferrous Metals Demand	PJ	0.5	0.5	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.8
Other Non Metallic Minerals Demand	PJ	29.2	24.5	24.3	26.6	27.5	28.3	29.3	30.3	31.4	32.5	33.6
Rail Freight	tkm*10^6	2018.6	2264.6	2485.4	2714.5	2964.2	3191.8	3425.9	3660.0	3894.1	4128.2	4362.3
Rail Passengers Heavy	pkm*10^6	3834.4	3752.5	3998.1	4200.0	4400.0	4510.6	4668.5	4826.4	4984.2	5142.1	5300.0
Rail Passengers Light	pkm*10^6	528.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

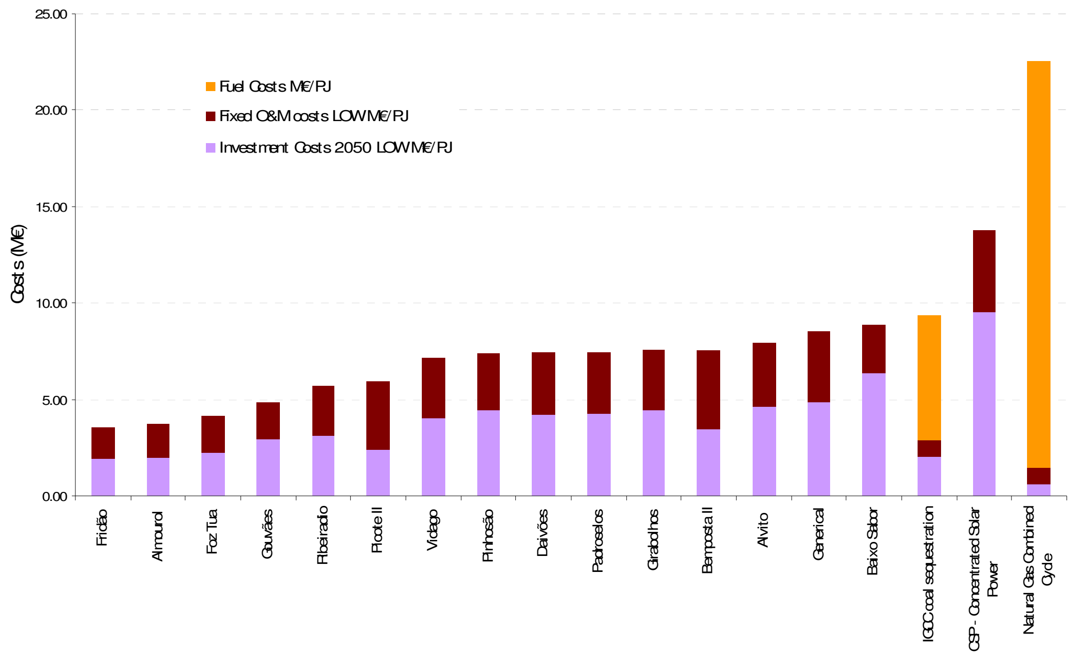
Final energy and material demand category	Unit	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Road Bus Intercity	pkm*10^6	8002.0	6968.5	7976.5	8376.6	8390.9	8598.7	8817.3	9035.9	9254.5	9473.1	9691.6
Road Bus Urban	pkm*10^6	3819.0	3515.6	3075.9	2800.0	2500.0	2136.0	1800.7	1465.3	1129.9	794.6	459.2
Road Car Long Distance	pkm*10^6	12954.2	26542.7	38951.7	47816.3	55968.7	68637.5	79367.7	90098.0	100828.2	111558.5	122288.8
Road Car Short Distance	pkm*10^6	61903.6	59084.6	61799.7	67213.2	70616.0	71789.5	74344.8	76900.1	79455.5	82010.8	84566.2
Road Freight	tkm*10^6	17327.8	22282.3	24106.2	26328.2	28750.2	31826.2	34515.3	37204.3	39893.4	42582.5	45271.6
Road Moto	pkm*10^6	2877.3	2724.2	2769.5	2814.7	2860.0	2825.9	2831.5	2837.1	2842.7	2848.3	2853.9
Residential Cloth Drying	PJ	0.4	0.4	0.5	0.6	0.8	1.0	1.2	1.2	1.3	1.3	1.4
Residential Cloth Washing	PJ	3.9	4.7	5.1	5.4	5.6	5.8	6.0	6.2	6.4	6.7	7.0
Residential Cooking	PJ	19.8	21.4	22.3	23.0	23.7	24.5	25.3	26.2	27.2	28.3	29.5
Residential Dish Washing	PJ	1.2	3.7	4.6	5.9	7.4	8.8	9.2	9.5	9.9	10.3	10.7
Residential Lighting	PJ	5.4	5.8	6.3	7.1	7.9	8.7	9.6	9.9	10.3	10.7	11.2
Residential Other Electric	PJ	10.5	12.2	13.7	15.5	17.6	20.0	21.8	22.5	23.4	24.3	25.3
Residential Refrigeration	PJ	7.4	8.7	9.6	10.2	11.0	11.8	12.7	13.1	13.6	14.2	14.7
Comercial Space Heating	PJ	33.2	50.1	55.1	55.2	55.4	55.4	55.5	55.4	55.4	55.5	55.5
Comercial Space Cooling	PJ	1.8	2.4	2.8	3.6	4.5	5.3	6.1	6.3	6.3	6.4	6.4
Comercial Water Heating	PJ	4.6	2.6	2.9	3.1	3.3	3.5	3.8	3.9	4.1	4.4	4.6
Residential Space Heating	PJ	15.1	20.3	23.9	28.0	31.0	34.7	37.1	39.6	42.4	45.2	48.2
Residential Space Cooling	PJ	0.1	0.4	1.4	1.0	1.4	1.8	2.1	2.2	2.3	2.4	2.5
Residential Water Heating	PJ	13.5	16.7	19.7	21.3	22.5	22.9	22.6	22.3	22.1	21.8	21.5

B. Annex II

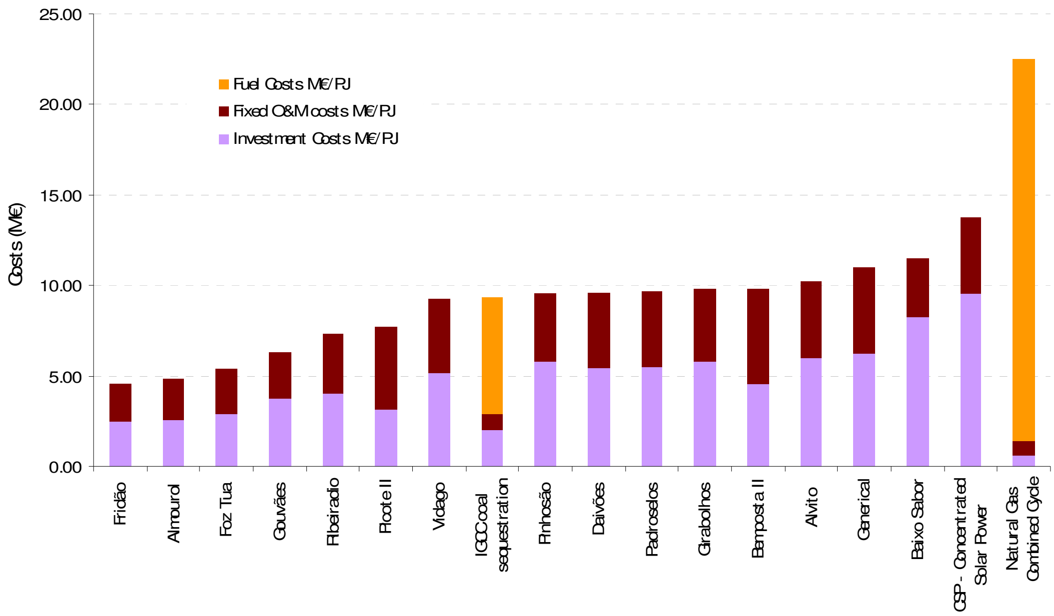
Supply curves for selected electricity production technologies



Annex II Figure 1 – Supply curve for the REF scenario of selected technologies for 2050



Annex II Figure 2 - Supply curve for the LOW scenario of selected technologies for 2050



Annex II Figure 3 - Supply curve for the HIGH scenario of selected technologies for 2050

Note: when analyzing these figures please note that annualized unit production costs are not the sole decision variable for TIMES_PT model: the differential availability factors in different seasons also has an impact on the decision. For instance, in the HIGH scenario, CSP plants are competitive with hydropower since the last one has extremely low availability factors in summer. Note that CCS technologies also compete in terms of production costs but are limited to storage capacity of CO_2.